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COMPUTER SIMULATION OF ARTILLERY SAFING AND ARMING MECHANISM IN AEROBALLISTIC ENVIRONMENT (INVOLUTE GEAR TRAIN AND STRAIGHT-SIDED VERGE RUNAWAY ESCAPEMENT)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A computer simulation was developed for a complete artillery safing and arming (S&A) mechanism which must operate in a projectile that experiences spin, precession, and nutation. This mechanism contains a straight-sided verge run-away escapement, a two pass involute step-up gear train, and a spin driven rotor. The mathematical model treats three motion regimes of the associated escapement (i.e., coupled motion, free motion, and impact). The computer program is well adapted to parametric studies, and it allows the use of pallets
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20. ABSTRACT (cont)

with arbitrarily selected centers of mass. Also, when actual aeroballistics data are used, it determines the behavior of the S&A mechanism in a projectile with pathological motion.

A sample simulation, with the dimensions of the M739 S&A mechanism, was run at 30,000 rpm with small precession and nutation velocities. It showed essentially the same number of turns-to-arm when only spin is present.

CONTENTS

INTRODUCTION

A computer simulation was developed for a complete artillery safing and arming (S&A) mechanism containing a straight-sided verge runaway escapement, a two pass involute step-up gear train, and a spin driven rotor which must operate in a projectile that experiences spin, precession, and nutation.

Top views of the mechanism planes of the two possible configurations are shown in figures 1 and 2. The position of this mechanism plane with respect to a projectile which experiences the aeroballistic motion is shown in figure 3.

While the basic ideas concerning the three motion regimes of the runaway escapement (coupled motion, free motion, and impact) are identical to those developed for the verge type runaway escapement (ref 1), the presence of the three dimensional projectile kinematics makes it necessary to consider three dimensional force and moment equations for all mechanism components in order to derive the mathematical models for the motion regimes.

The following briefly outlines the course of the derivation of the mathematical models:

1. Kinematics of Aeroballistic Systems: Absolute angular velocities and accelerations in terms of component-fixed and projectile-fixed coordinate systems (app A)

2. Angular Momentum and Its Derivatives in Various Coordinate Systems: Three dimensional moment equations in various coordinate systems (app B)

3. Absolute Acceleration of the Geometric Center C of the Mechanism Plane (app C)

4. Dynamics of Rotor Driven S&A Mechanism with a Two Pass Involute Gear Train and a Verge Runaway Escapement Operating in an Aeroballistic Environment: The derivations of the equations of motion for both entrance and exit coupled motion, free motion, and impact regimes are contained in the appendix. Expressions for all types of contact forces are given. The pivot friction forces are treated conservatively (refs 1 and 2). The change of direction of the friction forces and torques in the gear train due to a motion reversal of the mechanism are handled by appropriate sign change of the coefficient of friction (app D).

5. Projectile Kinematics: Since at the present time actual aeroballistic data are not available for incorporation into the program, a set of appropriate expressions, which allows certain simulation runs, has been provided (app E).

6. Computer Program SAEROV: The listing of the program also contains a sample output (app F).

To understand the derivations in the appendixes, it is suggested that references 1 through 5 be consulted concerning the work on gear trains as well as rotor and constant torque driven S&A mechanisms which contain pin pallet and verge type runaway escapements. For general background and kinematics, reference

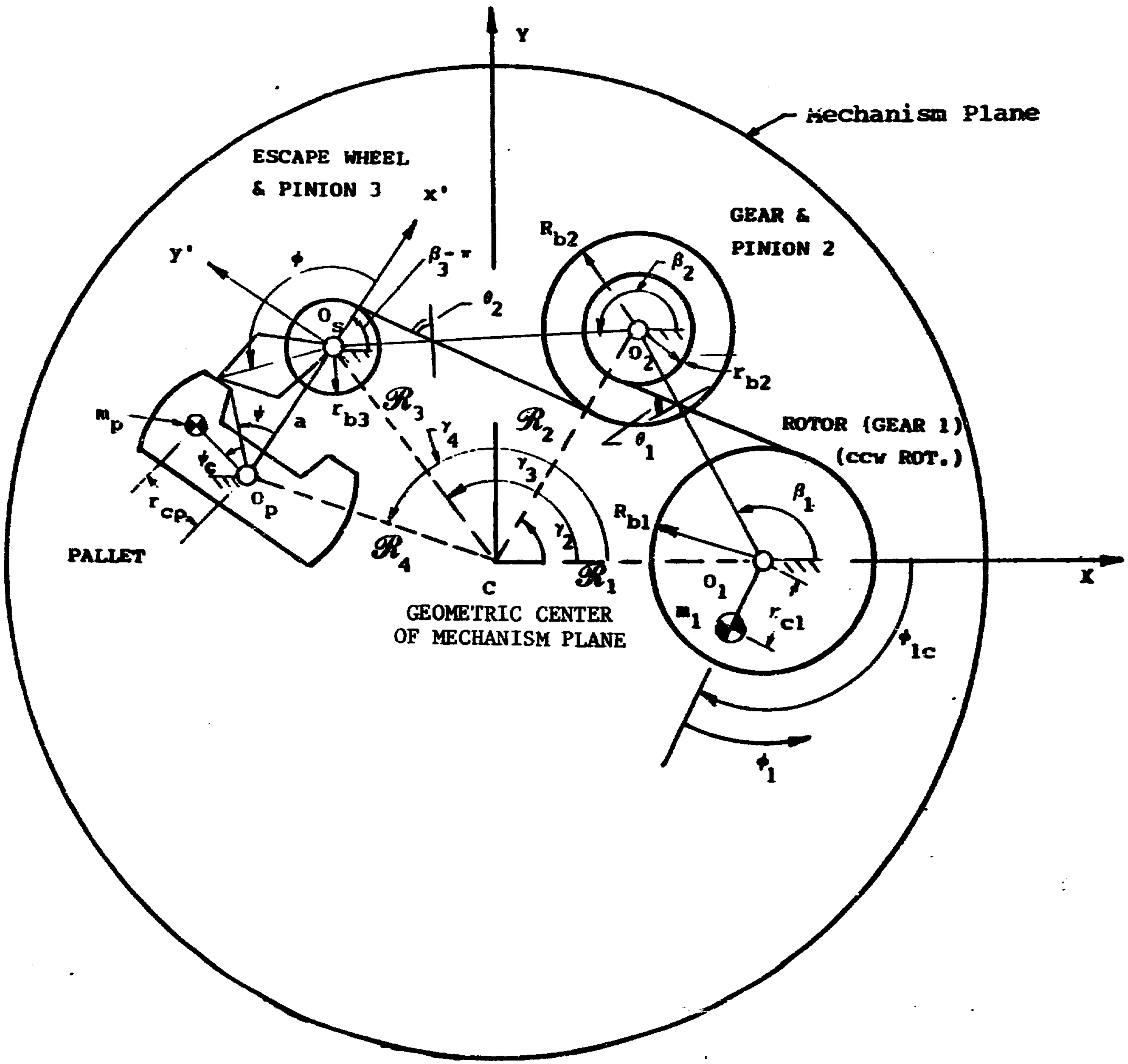


Figure 1. Rotor driven S&A device with verge, configuration no. 1

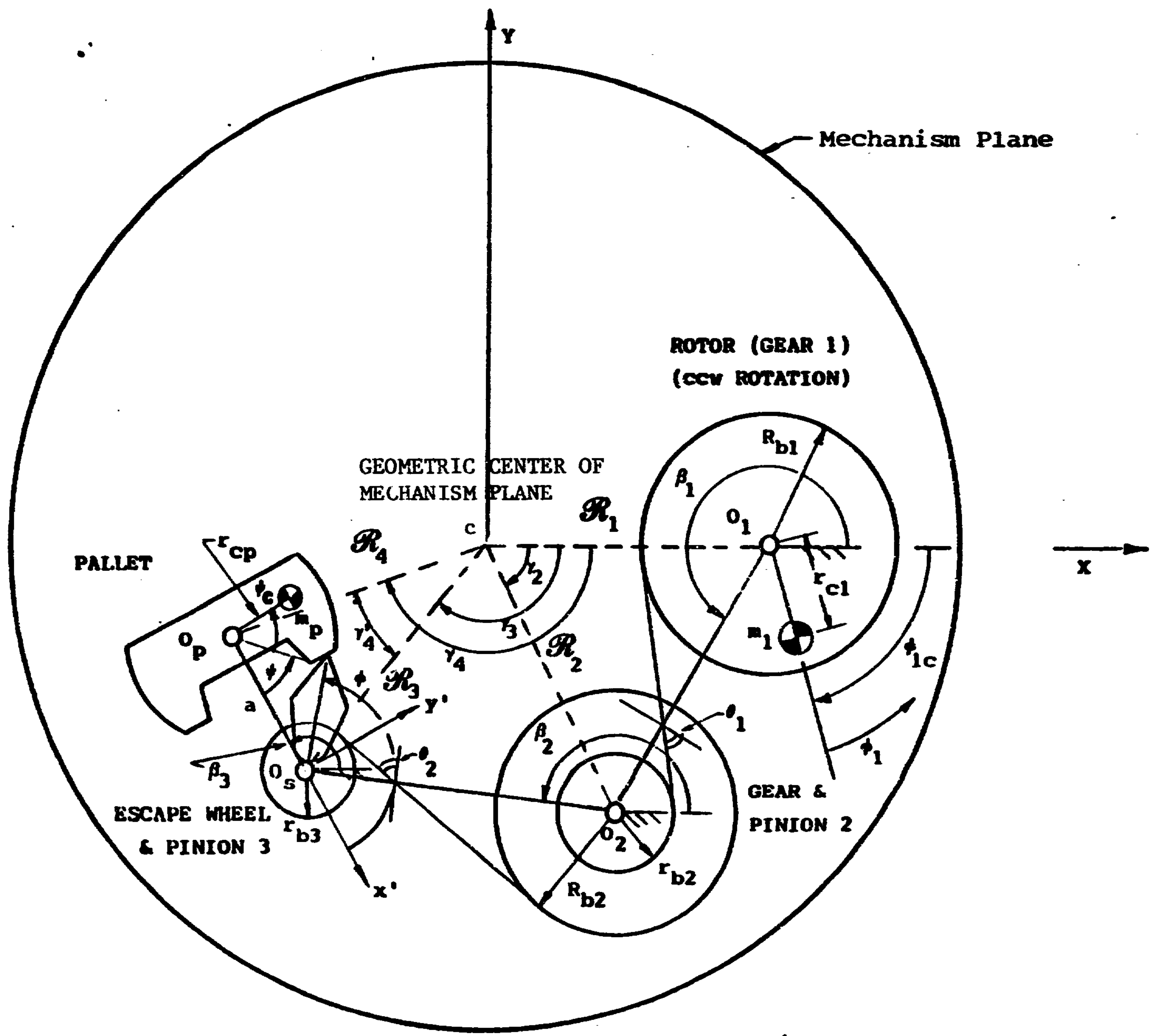
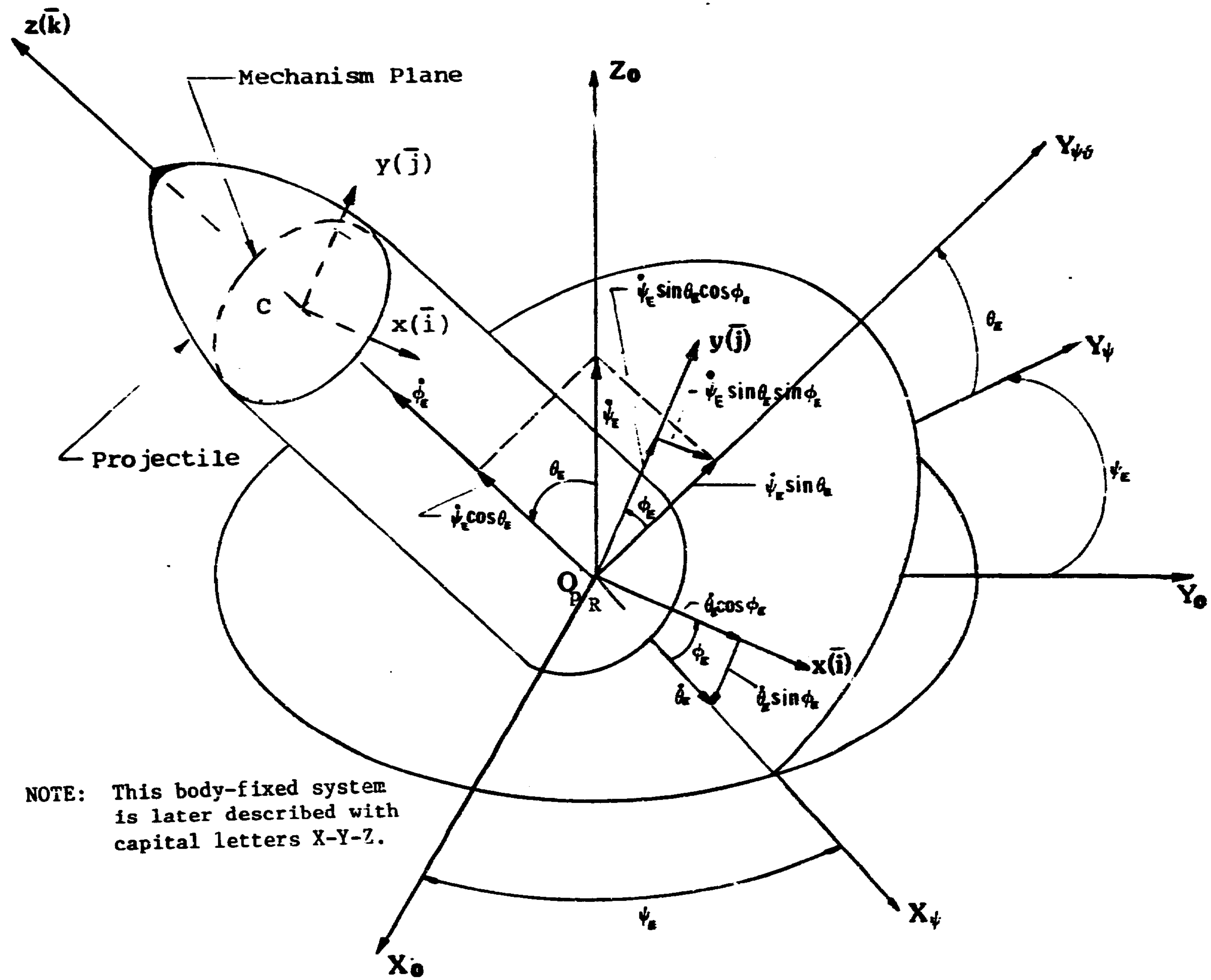


Figure 2. Rotor driven S&A device with verge, configuration no. 2



NOTE: This body-fixed system is later described with capital letters X-Y-Z.

Figure 3. Mechanism plane in projectile which experiences aeroballistic motion

6 is recommended. For the understanding of three dimensional rigid body dynamics as well as the relationships between the non-orthogonal coordinates by which the aeroballistic motion is expressed and the orthogonal component-fixed and projectile-fixed coordinate systems used, references 7 and 8 are suggested.

DESCRIPTION OF COMPUTER PROGRAM SAEROV

With the exception of the inclusion of the aeroballistic kinematics, the programming schemes which make it possible to distinguish between entrance and exit coupled motion, free motion, and impact run parallel to those given in reference 1. (This reference lists the control details applicable to the separation of entrance and exit coupled motion. For other control details, see references 2 through 5.)

The main program starts with the reading in and writing of all relevant physical data. This is followed by the computation of gear ratios, fuze body angles, gear train constants, and earliest and latest possible values of the gear angles by way of subroutine ALFA, as well as the initialization of the gear angles. The simulation begins with entrance-coupled motion at a starting angle PHID, which represents that angle ϕ of the escape wheel that is associated with the approximate center of the entrance working surface of the pallet. This angle then corresponds to a cumulative escape wheel angle PHITOT of 0 degree.

Coupled Motion (Location 1)

Regardless of whether entrance- or exit-coupled motion takes place, differential equation D-513 must be solved. (The difference between entrance and exition motion is set by the value of the signum function s_7 as used in the computations of parameters A_{16}, A_{21}, A_{29}, A_{33}, A_{36}, and A_{51}.) To this end, the main program calls on an available fourth-order Runge-Kutta routine.[1] The main purpose of the subroutine FCT is to present the second-order differential equation in terms of two first-order ones to RKGS. PHI(1) and PHI(2) represent the angle ϕ and the angular velocity $\dot{\phi}$, respectively. The computation of all parameters of the differential equation takes place by way of subroutine FCT, which itself calls on subroutine KINEM and AFIVE. The latter subroutine calls both on subroutine ACCEL, which depends on subroutine AERO, as well as on the sequential subroutines AWON, CWON, ATWO, CTWO, ATHREE, CTHREE, AFOUR, and CFOUR.

The subroutine KINEM computes current values of g, ψ and $\dot{\psi}$ (ref 1, app C) as well as the moment arms A_1', B_1', C_1', and D_1' (ref 1, app D).

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[1] RKGS Routine, IBM System/360 Scientific Subroutine Package (360A-CM-OX3), Version III.

Subroutine AFIVE computes various gear mesh parameters and instantaneous mesh contact angles, as well as the signum functions s_1, s_2, s_3, s_4, s_5, and s_7. In addition, the parameters A_1 to A_{120} and C_1 to C_{72} (app D) are obtained with the previously mentioned subroutines.[2] The gear-indexing operation (ref 4) is performed with the help of the angle ϕ.

The instantaneous rotor angle $\phi_{1C} + N_{31}\phi_T$ of the coupled motion differential equations must be expressed in subroutine FCT. Recall that ϕ_{1C} is the initial rotor angle; ϕ_T is the total angle of rotation of the escape wheel. Since the angle ϕ with the Runge-Kutta variable PHI(1) varies between approximately 134 and 144 degrees during entrance-coupled motion and between 209 and 216 degrees during exit-coupled motion, the total escape wheel angle ϕ_T can only be obtained by continuously adding the increments due to each cycle of Runge-Kutta computations. Therefore

$$\phi_T = \phi_{TOT} + \Delta\phi \tag{1}$$

where

ϕ_{TOT} = total escape wheel angle up to a certain Runge-Kutta cycle. (This is represented by PHITOT in the program.)

$\Delta\phi$ = increment of escape wheel during this Runge-Kutta cycle.

The increment $\Delta\phi$ is calculated as the difference between the latest value of PHI(1) and its previous one which has been stored as PHIPR. In this manner, equation 1 becomes

$$\phi_T = \text{PHITOT} + \text{PHI}(1) - \text{PHIPR} \tag{2}$$

Subroutines associated with AFIVE also decide on the values of I_{PR} and I_{1R} as required by equations D-134 and D-135 as well as equations D-409 and D-410 (app D). The associated conditional statements assign the larger values for these combined moments of inertia whenever the product of the angular velocity and the angular acceleration is positive; i.e., both quantities have the same sign.

The associated subroutine OUTP is responsible for printing out the results ϕ, $\dot{\phi}$, and $\ddot{\phi}$, together with the current values of time, g, ψ, $\dot{\psi}$, and PHITOT. Further all coupled motion contact forces are calculated according to equations D-520, D-525, D-527, and D-529, and the maximum values of these forces during one arming cycle are determined.

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[2] The program uses the symbols AA1, etc. throughout. This should not be confused with the symbols AA_{16} to AA_{51} which are first used in the combined exit-coupled motion differential equation (D-278).

Free Motion (Location 5)

The differential equations of free motion, as given by equation D-530 for the pallet and equation D-531 for the combined escape wheel-gear train-rotor system, are again solved by the Runge-Kutta routine. To obtain the magnitudes of the variables ϕ and ψ, as well as their derivatives at identical times, the two independent second-order differential equations are transformed into four simultaneous first order equations. (While only the two first-order equations associated with each of the two variables are actually coupled, the routine treats all four as if they were coupled and, therefore, produces solutions for identical time increments.) These four expressions, which are presented in subroutine FCTF, are of the following form:

$$DX(1) = X(2) : (= \dot{\phi}) \tag{3}$$

$$DX(3) = X(4) : (= \dot{\psi}) \tag{4}$$

$$DX(2) = \frac{1}{A_{117}} \left[-A_{118}(X(2))^2 - A_{119}X(2) + A_{120} \right] : (= \ddot{\phi}) \tag{5}$$

$$DX(4) = \frac{1}{I_{PR}} \left[-A_{32}(X(4))^2 - A_{31}X(4) - A_{116} + m_p r_{cp}(K_x \sin\beta - K_y \cos\beta) \right] : (= \ddot{\psi}) \tag{6}$$

The subroutine FCTF also calls on subroutine AFIVE for the computation of all gear-related parameters.[3]

The associated subroutine OUTPF computes the free motion contact forces according to equations D-537 and D-539 and finds their maxima. In addition, a continuous count of PHITOT is provided by OUTPF. This angle as well as time, ϕ, $\dot{\phi}$, ψ, $\dot{\psi}$, and the contact forces are printed out. The same routine also makes the decision of whether or not to remain in free motion. The sensing variables f and g' = GP are used for this purpose (ref 1, eqs E-4 and E-5).

Impact (Location 15)

The subroutine IMPACT uses the pre-impact values $\dot{\phi}_i$, and $\dot{\psi}_i$ of the angular velocities and computes their post-impact values $\dot{\phi}_f$ and $\dot{\psi}_f$ according to equations D-540 and D-541 (app D). (Note that the moment of inertia of the escape wheel is now expressed according to equation D-542 (app D), which refers the rotor as well as the gear train inertias to the escape wheel.)

[3] Whenever $I_{PR} = 0$, the simulation stops because of the division by zero. Should this occur, FCTF prints "IPR EQUALS ZERO--SIMULATION TERMINATED."

Reversal of Gear Train Motion Due to Impact

If the impact torque on the escape wheel is sufficiently large, the motion of the gear train may be temporarily reversed; i.e., the escape wheel angular velocity $\dot{\phi}$ may become negative. This would cause the friction forces between the gear teeth and at the various gear pivots to be reversed in direction. (The normal forces between the gear teeth remain unaffected, and the normal bearing forces are obtained in the usual manner.) This change in the direction of the friction forces is expressed for both coupled and free motion by letting the coefficient of friction μ of all gear train components become negative (app E of ref 2). This is accomplished in subroutine AFIVE by the following use of the signum function $\dot{\phi}/|\dot{\phi}|$:

$$MU = ABS(MU) * \dot{\phi}/|\dot{\phi}| \tag{7}$$

(The coefficient of friction associated with the escapement interface and the pallet pivot is called μ_1 and is read into the programs as MU1.) Any motion reversal at these surfaces is accounted for by the signum functions s_4 and s_5, respectively.

Termination of Computations

Computations are terminated whenever the geared motion of the rotor ends. This corresponds to ϕ = PHICUTD. The duration of the subsequent unretarded motion of the rotor is assumed to be negligible.

COMPUTER SIMULATION OF EXAMPLE MECHANISM

The mechanism which has been simulated is that of a modified S&A device of the M739 fuze. It has configuration no. 2 (fig. 2) and contains a newly-designed involute gear train. While this gear train has the same gear ratio and individual center distances as the original design, each of the meshes now has unity contact ratio.[4] The simulation of this mechanism was accomplished with the help of computer program SAEROV (app F). It was run for 30,000 rpm to obtain maximum contact forces and used the projectile kinematics (app B).

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[4] Both meshes were designed with the help of computer programs INVOL11 and GEARPARAM2, originally shown in Progress Report No. 11 of the "Development of Automated Design Optimization Technique for Safety and Arming Devices" (Contract No. DAAK10-79-C-0251, January 15, 1981). Copies of this report may be obtained from either F. R. Tepper, ARRADCOM or G. G. Lowen, The City College of New York.

The following shows the input requirements of the program, explains the various output data, and discusses the manner in which the "number-of-turns-to-arm" is obtained for a given spin velocity.

Input Data

The first portion of the output repeats all input data, which represent the mechanism parameters of the M739 fuze. These are listed both as computer variables and as symbols, according to the various appendixes of this report as well as reference 1.

Escapement Parameters

A = a = 0.226 in. (5.740 mm) = distance between pivots O_p and O_s (fig. 2)

B = b = 0.168 in. (4.267 mm) = escape wheel radius

C = c = 0.13138 in. (3.337 mm) = pallet radius as defined by figure F-1 of appendix F, reference 1

ALPHEN = α_{en} = 43.352 deg = entrance working surface angle

ALPHEX = α_{ex} = 29.2981 deg = exit working surface angle

NT = 4 = number of escape wheel teeth spanned by verge

CONFIG = 2 = configuration no. 2 (fuze body configuration no. 2 in ref 1, app B)

EREST = e_r = 0 = coefficient of restitution

LAMBDA = λ = 92.93 deg = angle between entrance and exit pallet radii (ref 1, app F, fig. F-1)

N = 22 = number of escape wheel teeth

For details of the above nomenclature, see reference 1, appendixes C, E, and F.

Mass Parameters of Components

M1 = m_1 = 0.3165 x 10^{-4} lb-sec^2/in. (5.552 x 10^{-3} kg) = mass of rotor

M2 = m_2 = 0.3275×10^{-5} lb-sec^2/in. (5.745×10^{-4} kg) = mass of gear and pinion no. 2

M3 = m_3 = 0.2631×10^{-5} lb-sec^2/in. (4.615×10^{-4} kg) = mass of escape wheel and pinion no. 3

MP = m_p = 0.1640×10^{-5} lb-sec^2/in. (2.877×10^{-4} kg) = mass of pallet

IXX1 = $I_{\xi\xi_1}$ = 0.1222×10^{-5} in.-lb-sec^2 (1.383×10^{-7} kg - m^2) = moment of inertia of rotor with respect to ξ_1-axis (through center of mass, see fig. A-3).

IEE1 = $I_{\eta\eta_1}$ = 0.1234×10^{-5} in.-lb-sec^2 (1.397×10^{-7} kg-m^2) = moment of inertia of rotor with respect to η_1-axis

IZZ1 = $I_{\zeta\zeta_1}$ = 0.1967×10^{-5} in.-lb-sec^2 (2.226×10^{-7} kg-m^2) = moment of inertia of rotor with respect to pivot axis (ζ_1-axis)

IXE1 = $I_{\xi\eta_1}$ = -0.1012×10^{-6} in.-lb-sec^2 (-1.145×10^{-8} kg-m^2) = ξ_1-η_1 product of inertia of rotor

IZX1 = $I_{\zeta\xi_1}$ = -0.3656×10^{-7} in.-lb-sec^2 (-4.137×10^{-9} kg-m^2) = ζ_1-ξ_1 product of inertia of rotor

IEZ1 = $I_{\eta\zeta_1}$ = -0.1770×10^{-7} in.-lb-sec^2 (-2.003×10^{-9} kg-m^2) = η_1-ζ_1 product of inertia of rotor

IX2 = I_{x2} = 0.2944×10^{-7} in.-lb-sec^2 (3.389×10^{-9} kg-m^2) = moment of inertia of gear and pinion no. 2 (about axis normal to pivot axis)

IY2 = I_{y2} = 0.2944×10^{-7} in.-lb-sec^2 (3.389×10^{-9} kg-m^2) = moment of inertia of gear and pinion no. 2 (about axis normal to pivot axis and perpendicular to x_2-axis)

IZ2 = I_{z2} = 0.4026×10^{-7} in.-lb-sec^2 (4.556×10^{-9} kg-m^2) = moment of inertia of gear and pinion no. 2 with respect to pivot axis

IXS = I_{xs} = 0.2038×10^{-7} in.-lb-sec^2 (2.307×10^{-9} kg-m^2) = moment of inertia of escape wheel and pinion no. 3 (about axis normal to pivot axis)

IYS = I_{ys} = 0.2038×10^{-7} in.-lb-sec^2 (2.307×10^{-9} kg-m^2) = moment of inertia of escape wheel and pinion no. 3 (about axis normal to pivot axis and perpendicular to x_s-axis)

IZS = I_{zs} = 0.2125×10^{-7} in.-lb-sec^2 (2.405×10^{-9} kg-m^2) = moment of inertia of escape wheel and pinion no. 3 with respect to pivot axis

IXXP = $I_{\xi\xi_p}$ = 0.1721×10^{-8} in.-lb-sec^2 (1.948×10^{-10} kg-m^2) = moment of inertia of pallet with respect to ξ_p-axis (through center of mass, see fig. A-2)

IEEP = $I_{\eta\eta_p}$ = 0.3038×10^{-8} in.-lb-sec^2 (3.438×10^{-10} kg-m^2) = moment of inertia of pallet with respect to η_1-axis

IZZP = $I_{\zeta\zeta_p}$ = 0.1951×10^{-7} in.-lb-sec^2 (2.028×10^{-9} kg-m^2) = moment of inertia of pallet with respect to pivot axis (ζ_p-axis)

IXEP = $I_{\xi\eta_p}$ = 0. = ξ_p-η_p product of inertia of pallet

IZXP = $I_{\zeta\xi_p}$ = 0. = ζ_p-ξ_p product of inertia of pallet

IEZP = $I_{\eta\zeta_p}$ = 0. = η_p-ζ_p product of inertia of pallet

General Parameters

RC1 = r_{c1} = 0.0567 in. (1.463 mm) = distance from pivot of rotor to its center of mass

RCP = r_{cp} = 0 = pallet eccentricity

RHOP = ρ_p = 0.0227 in. (0.577 mm) = pallet pivot radius

RPM = 30,000 = spin rate

PHI1CD = ϕ_{1c} = -120.134 deg = rotor angle in starting position (fig. 2)

PSICCD = ψ_c = 0 deg = eccentricity angle of pallet

PHID = 139 deg = escape wheel starting angle of initial coupled motion

PHICUTD = 1485 deg = cumulative escape wheel angle obtained from product of total engaged rotor rotation and gear ratio. The total rotor rotation for the M739 fuze is 46.41 deg, while the gear ratio is 32. Thus, PHICUTD = 46.41 x 32 = 1485 deg.

MU = μ = 0.10 = coefficient of friction of gear train (pivots and tooth-to-tooth contacts) and escape wheel pivot (constant for a computer run)

MU1 = μ_1 = 0.10 = coefficient of friction of pallet-escape wheel interface and pallet pivot (constant for a computer run)

LU = LL = L_U = L_L = 0.285 in. (7.24 mm) = one-half of mean distance between bearing plate surfaces

Gear Parameters

PSUBD1 = P_{d1} = 80 = diametral pitch of mesh no. 1 (rotor and pinion no. 2)

PSUBD2 = P_{d2} = 100 = diametral pitch of mesh no. 2 (gear no. 2 and escape wheel pinion)

NG1 = N_{G1} = 64 = number of teeth of rotor (full gear no. 1)

NG2 = N_{G2} = 36 = number of teeth of gear no. 2

NP2 = N_{P2} = 9 = number of teeth of pinion no. 2

NP3 = N_{P3} = 8 = number of teeth of pinion no. 3 (escape wheel pinion)

CAPRP1 = R_{P1} = 0.41214 in. (10.468 mm) = pitch radius of gear no. 1 (rotor)

CAPRP2 = R_{P2} = 0.19039 in. (4.836 mm) = pitch radius of gear no. 2

RP2 = r_{p2} = 0.05796 in. (1.472 mm) = pitch radius of pinion no. 2

RP3 = r_{p3} = 0.04231 in. (1.075 mm) = pitch radius of pinion no. 3 (escape wheel pinion)

THETA1 = θ_1 = 24.215 deg = pressure angle of mesh no. 1

THETA2 = θ_2 = 27.326 deg = pressure angle of mesh no. 2

R1 = $\mathcal{R}_1$ = 0.250 in. (6.350 mm) = distance of rotor pivot from spin axis

R2 = $\mathcal{R}_2$ = 0.317 in. (8.052 mm) = distance of pivot of gear and pinion set no. 2 from spin axis

R3 = $\mathcal{R}_3$ = 0.309 in. (7.849 mm) = distance of pivot of escape wheel from spin axis

R4 = $\mathcal{R}_4$ = 0.304 in. (7.722 mm) = distance of pivot of pallet from spin axis

RHO1 = ρ_1 = 0.03075 in. (0.781 mm) = pivot radius of rotor

RHO2 = ρ_2 = 0.015 in. (0.381 mm) = pivot radius of gear and pinion no. 2

RHO3 = ρ_3 = 0.015 in. (0.381 mm) = pivot radius of escape wheel

RHOF1 = ρ_{F1} = 0.055 in. (1.397 mm) = friction thrust radius of rotor (for computation of friction thrust radius see p 268 in ref 8)

RHOF2 = ρ_{F2} = 0.0294 in. (0.747 mm) = friction thrust radius of gear and pinion no. 2

RHOF3 = ρ_{F3} = 0.0294 in. (0.747 mm) = friction thrust radius of escape wheel and pinion no. 3

RHOF = ρ_F = 0.1138 in. (2.890 mm) = friction thrust radius of pallet

CAPRB1 = R_{b1} = 0.37588 in. (9.547 mm) = base radius of gear no. 1

CAPRB2 = R_{b2} = 0.16915 in. (4.296 mm) = base radius of gear no. 2

RB2 = r_{b2} = 0.05286 in. (1.343 mm) = base radius of pinion no. 2

RB3 = r_{b3} = 0.03759 in. (0.955 mm) = base radius of escape wheel pinion

CAPRO1 = R_{01} = 0.41425 in. (10.522 mm) = outside radius of gear no. 1

CAPRO2 = R_{02} = 0.19404 in. (4.929 mm) = outside radius of gear no. 2

RO2 = r_{02} = 0.07670 in. (1.948 mm) = outside radius of pinion no. 2

RO3 = r_{03} = 0.05580 in. (1.417 mm) = outside radius of escape wheel pinion

J1 = J_1 = 0 = initialization parameter for mesh no. 1 [The zero value corresponds to earliest possible contact of mesh (ref 3).]

J2 = J_2 = 0 = initialization parameter for mesh no. 2

Projectile Parameters

RX, RY, RZ =coordinates of geometric center C of mechanism plane with respect to projectile center of mass, expressed in projectile fixed coordinate system with origin at point O_{PR} [This system is parallel to mechanism plane fixed XY system (figs. 1 through 3 and C-1).]

RX = R_x = 0.001 in. (0.0254 mm)

RY = R_y = 0.001 in. (0.0254 mm)

RZ = R_z = 20.0 in. (508 mm)

Projectile Kinematics

The projectile kinematics are programmed in subroutine AERO according to the expressions given in appendix E. The following parameters are incorporated:

For equation E-5, KP = K_p = 100

For equation E-8, THETIN = 8 deg
TV = 2 deg
KN = 10
DDZ = $\ddot{Z}$ = -386.4 x 10 (corresponds to a 10-g deceleration)

Output Data

The data blocks following the input data represent the results of various computations.

Fuze Geometry

The angles BETA1D = β_1 to BETA3D = β_3 and GAMMA2D = γ_2 to GAMMA4D = γ_4 are printed for checking purposes.

Coupled Motion

The first coupled motion output refers to the entrance side of the verge. For each time T of the coupled motion, the following variables are computed:

PHI = ϕ = instantaneous escape wheel angle (deg)

PHIDOT = $\dot{\phi}$ = escape wheel angular velocity (rad/sec)

G = g = pallet - escape wheel contact position (in.) (ref 1, app C, eq C-15)

PSID = ψ = pallet angle (deg)

PSIDOT = $\dot{\psi}$ = pallet angular velocity (rad/sec)

PHITOT = ϕ_T = cumulative escape wheel angle (deg)

F23 = F_{23} = normal contact force of gear no. 2 on pinion no. 3 (lb)

F12 = F_{12} = normal contact force of gear no. 1 on pinion no. 2 (lb)

PN = P_n = normal contact force between escape wheel and pallet (lb), computed according to equation D-529 in appendix D

PNPSI = P_n = normal contact force between escape wheel and pallet (lb), computed according to equation D-527 in appendix D (serves for checking)

DPHI2 = $\ddot{\phi}$ = escape wheel angular acceleration (rad/sec^2), Runge-Kutta output

Free Motion

The first free motion on the exit side follows the coupled motion on the entrance side of the verge. For each time T of the free motion, the following variables are evaluated:

PHI = ϕ = instantaneous escape wheel angle (deg)

PHIDOT = $\dot{\phi}$ = escape wheel angular velocity (rad/sec)

PSI = ψ = pallet angle (deg)

PSIDOT = $\dot{\psi}$ = pallet angular velocity (rad/sec)

FF12 = F_{F12} = normal contact force of gear no. 1 on pinion no. 2 for free motion (lb)

FF23 = F_{F23} = normal contact force of gear no. 2 on escape wheel pinion for free motion (lb)

Impact

The first exit impact follows the first exit free motion. Just preceding the IMPACT label, the program prints the values of VP = V_{TNi} and VS = V_{SNi} which stand for the pre-impact velocity components, normal to the verge face of both the pallet and escape wheel contact points (ref 1, app D, eq D-13). Subsequent to the IMPACT label, the following variables are evaluated:

PHI = ϕ = instantaneous escape wheel angle (deg), same as before impact

PHIDOT = $\dot{\phi}$ = post-impact escape wheel angular velocity (rad/sec)

PSI = ψ = pallet angle (deg), same as before impact

PSIDOT = $\dot{\psi}$ = post-impact pallet angular velocity (rad/sec)

PHITOT = ϕ_T = cumulative escape wheel angle (deg), same as before impact

VP = V_{TNf} = post-impact normal velocity component of pallet at contact point (ref 1, eq D-15)

VS = V_{SNf} = post-impact normal velocity component of escape wheel tooth at contact point (ref 1, eq D-13)

In the present program, the post-impact VP is equal to VS since the coefficient of restitution is zero.

Number of Turns-to-Arm and Maximum Contact Forces

The number of turns-to-arm at 30,000 rpm is obtained with the help of that time T_{1485} which corresponds to the escape wheel angle PHICUTD = 1485 deg. Thus, with T_{1485} = 0.05094 sec,

$$\text{number of turns-to-arm} = \frac{30000}{60} \times 0.05094 = 25.47$$

The maximum non-impact contact forces for the total cycle, for both coupled and free motion, are listed at the end of the output.

CONCLUSIONS

While it was not the purpose of this investigation to undertake a parametric study of the mechanism for which the program was written, the program was sufficiently tested to confirm that such a study is possible. It may include variations in masses and moments of inertia of all components; variations in the locations of the centers of mass of the verge and the rotor; variations of gear, escapement, and fuze geometries; as well as various friction and coefficient of restitution conditions. In addition, the aeroballistic data can also be varied. This makes it possible to determine the functioning limits of the mechanism under pathological projectile flight conditions.

The present work reports only on a single test run using the M739 fuze S&A data with a system coefficient of friction of 0.1. This is assumed to be representative of actual test conditions since previous simulations of pin pallet escapements showed that the range of actual experimental results (with spin only) may be reproduced with coefficients of friction between 0.1 and 0.2, and a special lubricant is used in conjunction with the M739 fuze. This choice of coefficient of friction is proven by the good agreement with experimental results. A zero coefficient of restitution is used in the impact model (ref 1 and 2).

Previous high-speed motion picture observations of pin pallet escapements showed that the impacts were essentially inelastic and that a zero coefficient of

restitution was justified. Similar observations made on the detached lever escapement of the M577 fuze timer confirmed this.

The test run showed that for a spin rate of 30,000 rpm, together with small precession and nutation velocities chosen in the manner shown in appendix E, the number of turns-to-arm is essentially the same as that obtained in reference 6 where only spin was considered.

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APPENDIX A

KINEMATICS OF AEROBALLISTIC SYSTEMS

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ANGULAR VELOCITIES AND ACCELERATIONS IN TERMS OF PROJECTILE-FIXED COORDINATES

A projectile which experiences general aeroballistic motion, i.e. spin about an axis through its center of mass as well as precession and nutation of this spin axis with respect to its center of mass, is shown in figure A-1. (In the figure, the spin axis coincides with the geometric axis.)

The spin angle, spin velocity, and spin acceleration are expressed by the time dependent quantities ϕ_E, $\dot{\phi}_E$, and $\ddot{\phi}_E$. (The subscript E stands for the Euler angles, which are involved in this derivation.) Similarly, the kinematic quantities associated with the precession are ψ_E, $\dot{\psi}_E$, and $\ddot{\psi}_E$. The nutation variables are θ_E, $\dot{\theta}_E$, and $\ddot{\theta}_E$ (refs 7 and 8).

With spin, precession, and nutation angular velocity vectors, together with their associated angles (fig. A-1), orthogonal angular velocity components in terms of the projectile fixed x-y-z system may be obtained as follows:

Let

$$\bar{\omega}_{b/a} = \omega_x \bar{i} + \omega_y \bar{j} + \omega_z \bar{k} \tag{A-1}$$

where $\bar{\omega}_{b/a}$ represents the angular velocity of the projectile b with respect to the inertial frame a. Then

$$\omega_x = \dot{\theta}_E \cos \phi_E + \dot{\psi}_E \sin \theta_E \sin \phi_E \tag{A-2}$$

$$\omega_y = - \dot{\theta}_E \sin \phi_E + \dot{\psi}_E \sin \theta_E \cos \phi_E \tag{A-3}$$

$$\omega_z = \dot{\phi}_E + \dot{\psi}_E \cos \theta_E \tag{A-4}$$

The absolute angular acceleration of the projectile, i.e.,

$$\dot{\bar{\omega}}_{b/a} = \dot{\omega}_x \bar{i} + \dot{\omega}_y \bar{j} + \dot{\omega}_z \bar{k} \tag{A-5a}$$

is obtained by differention of the body fixed quantities with respect to time. Thus

$$\begin{aligned} \dot{\omega}_x = \ddot{\theta}_E \cos \phi_E - \dot{\theta}_E \dot{\phi}_E \sin \phi_E + \ddot{\psi}_E \sin \theta_E \sin \phi_E \\ + \dot{\psi}_E \dot{\theta}_E \cos \theta_E \sin \phi_E + \dot{\psi}_E \dot{\phi}_E \sin \theta_E \cos \phi_E \end{aligned} \tag{A-5b}$$

$$\begin{aligned} \dot{\omega}_y = - \ddot{\theta}_E \sin \phi_E - \dot{\theta}_E \dot{\phi}_E \cos \phi_E + \ddot{\psi}_E \sin \theta_E \cos \phi_E \\ + \dot{\psi}_E \dot{\theta}_E \cos \theta_E \cos \phi_E - \dot{\psi}_E \dot{\phi}_E \sin \theta_E \sin \phi_E \end{aligned} \tag{A-5c}$$

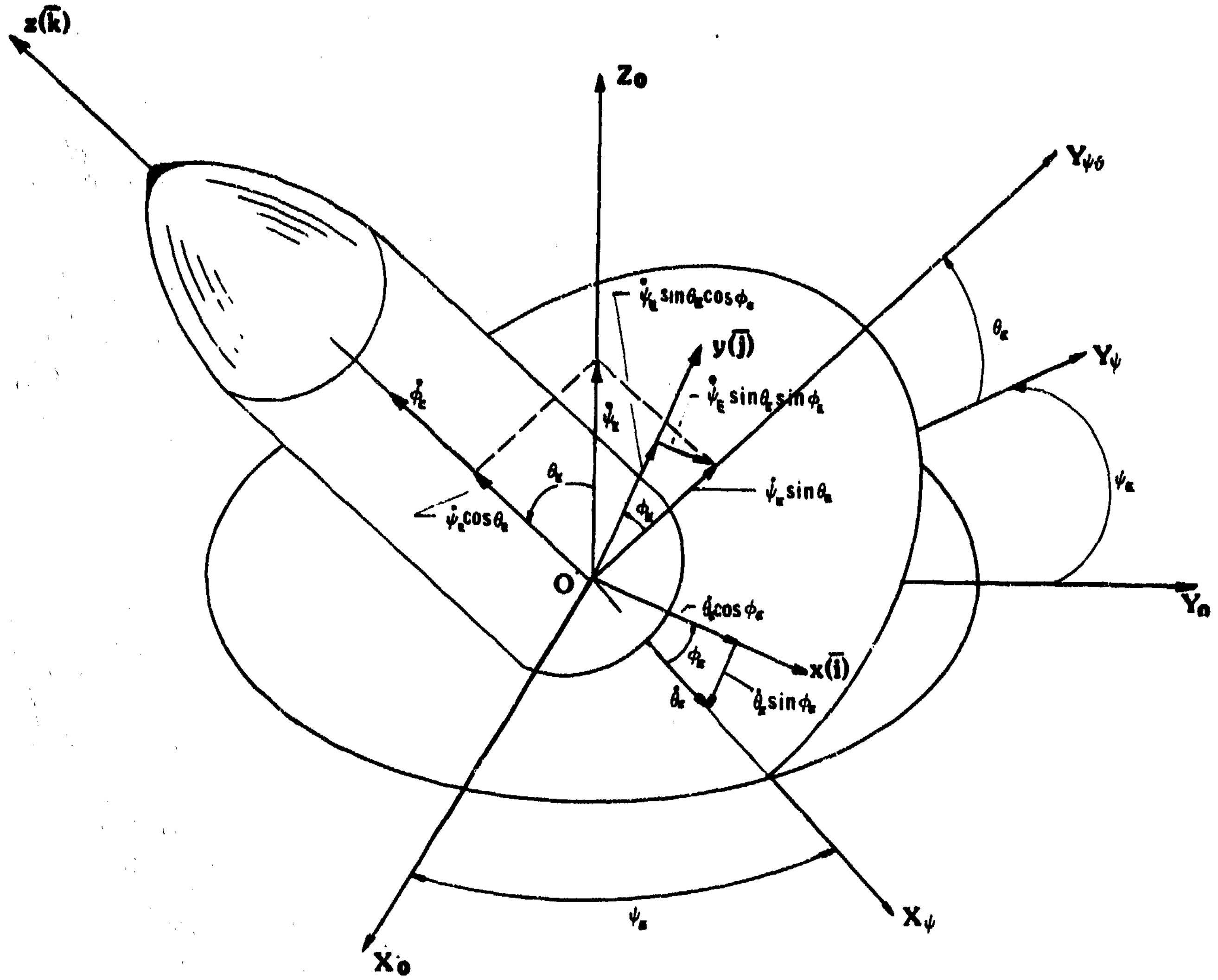

FIGURE A-1

PROJECTILE-FIXED x-y-z SYSTEM

Note: This system is later described with capital letters X-Y-Z

NOTE: This system is later described with capital letters X-Y-Z.

Figure A-1. Projectile-fixed x-y-z system

$$\dot{\omega}_z = \ddot{\phi}_E + \ddot{\psi}_E \cos \theta_E - \dot{\psi}_E \dot{\theta}_E \sin \theta_E \qquad \text{(A-5d)}$$

ANGULAR VELOCITIES AND ACCELERATIONS IN TERMS OF PROJECTILE-FIXED COORDINATES

Pallet-Fixed Coordinates

The relationship of the pallet-fixed $\xi_p - \eta_p - \zeta_p$ system with respect to the projectile fixed X-Y-Z and x'-y'-z' systems is shown in figure A-2 (ref 1).

The $\xi_p - \eta_p$ plane is parallel to the x'-y' and X-Y planes and contains the pallet center of mass C_p. The ζ_p-axis is parallel to the z and z' axes.

The pallet angles ψ and ψ_c are measured in the $\xi_p - \eta_p$ plane and are otherwise defined as in reference 1. Before determining the absolute angular velocity and acceleration of the pallet, a number of unit vectors should be defined. According to equations B-28 and B-29 of ref 1:

$$\bar{i}' = -\cos \beta_3 \bar{i} - \sin \beta_3 \bar{j} \qquad \text{(A-6)}$$

and

$$\bar{j}' = \sin \beta_3 \bar{i} - \cos \beta_3 \bar{j} \qquad \text{(A-7)}$$

Further, when expressed in the primed system, pallet fixed unit vectors become:

$$\bar{n}_{\xi_p} = \cos \beta \bar{i}' + \sin \beta \bar{j}' \qquad \text{(A-8)}$$

$$\bar{n}_{\eta_p} = -\sin \beta \bar{i}' + \cos \beta \bar{j}' \qquad \text{(A-9)}$$

where

$$\beta = \psi + \psi_c \qquad \text{(A-10)}$$

If equations A-6 and A-7 are substituted into the above expressions, after some trigonometric simplifications, the following expressions are obtained for the pallet fixed unit vectors in terms of the X-Y-Z system:

$$\bar{n}_{\xi_p} = -\cos \alpha' \bar{I} - \sin \alpha' \bar{J} \qquad \text{(A-11)}$$

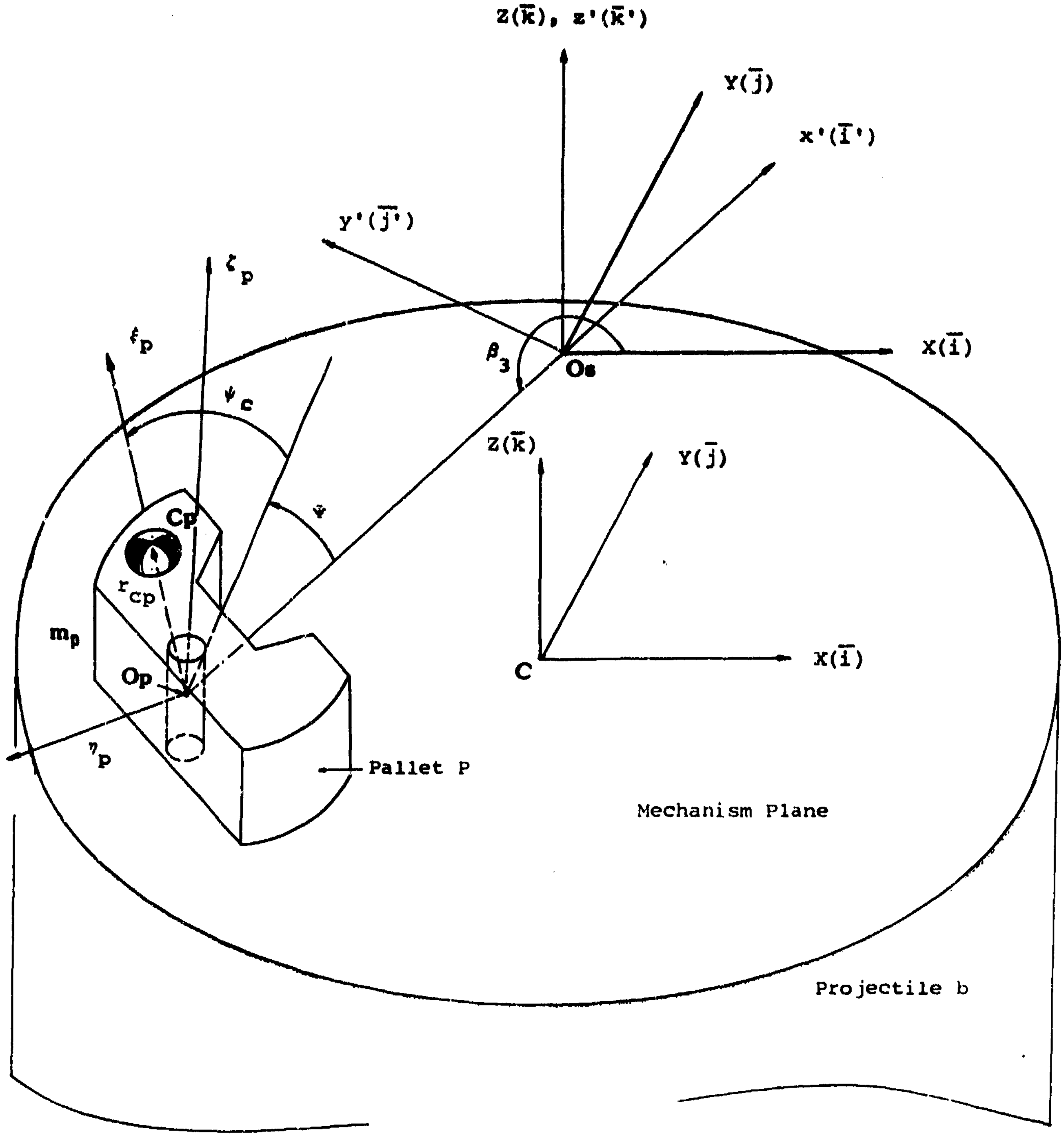

Figure A-2. Pallet-fixed ξ_p-η_p -ζ_p coordinate system

and

$$\bar{n}_{\eta_p} = \sin\alpha'\bar{i} - \cos\alpha'\bar{j} \tag{A-12}$$

where

$$\alpha' = \psi + \psi_c + \beta_3 \tag{A-13}$$

Because of the given parallel axes,

$$\bar{n}_{\zeta_p} = \bar{k}' = \bar{k} \tag{A-14}$$

If the relative angular velocity of the pallet P with respect to the projectile b is given by

$$\bar{\omega}_{p/b} = \dot{\psi}\,\bar{n}_{\zeta_p}, \tag{A-15}$$

then its absolute angular velocity $\bar{\omega}_{p/a}$ is given by

$$\bar{\omega}_{p/a} = \bar{\omega}_{p/b} + \bar{\omega}_{b/a} \tag{A-16}$$

To express equation A-16 in pallet-fixed terms, it is necessary to transform equation A-1 which gave $\bar{\omega}_{b/a}$. According to equations A-11 and A-12:

$$\bar{i} = -\cos\alpha'\,\bar{n}_{\xi_p} + \sin\alpha'\,\bar{n}_{\eta_p} \tag{A-17}$$

and

$$\bar{j} = -\sin\alpha'\,\bar{n}_{\xi_p} - \cos\alpha'\,\bar{n}_{\eta_p} \tag{A-18}$$

Thus, one obtains in the pallet fixed system:

$$\bar{\omega}_{b/a} = -[\omega_x\cos\alpha' + \omega_y\sin\alpha']\,\bar{n}_{\xi_p} + [\omega_x\sin\alpha' - \omega_y\cos\alpha']\,\bar{n}_{\eta_p} + \omega_z\,\bar{n}_{\zeta_p} \tag{A-19}$$

Finally, the absolute angular velocity of the pallet $\bar{\omega}_{p/a}$ becomes with equations A-15 and A-16:

$$\bar{\omega}_{p/a} = \omega_{\xi_p} \bar{n}_{\xi_p} + \omega_{\eta_p} \bar{n}_{\eta_p} + \omega_{\zeta_p} \bar{n}_{\zeta_p} \tag{A-20}$$

where

$$\omega_{\xi_p} = -(\omega_x \cos \alpha' + \omega_y \sin \alpha') \tag{A-21}$$

$$\omega_{\eta_p} = \omega_x \sin \alpha' - \omega_y \cos \alpha' \tag{A-22}$$

$$\omega_{\zeta_p} = \omega_z + \dot{\psi} \tag{A-23}$$

The absolute angular acceleration $\dot{\bar{\omega}}_{p/a}$ of the pallet is obtained by the differentiation with respect to time of the measure numbers of equation A-20, i.e.:

$$\dot{\bar{\omega}}_{p/a} = \dot{\omega}_{\xi_p} \bar{n}_{\xi_p} + \dot{\omega}_{\eta_p} \bar{n}_{\eta_p} + \dot{\omega}_{\zeta_p} \bar{n}_{\zeta_p} \tag{A-24}$$

where

$$\dot{\omega}_{\xi_p} = -\left(\dot{\omega}_x \cos \alpha' - \omega_x \dot{\psi} \sin \alpha' + \dot{\omega}_y \sin \alpha' + \omega_y \dot{\psi} \cos \alpha'\right) \tag{A-25}$$

$$\dot{\omega}_{\eta_p} = \dot{\omega}_x \sin \alpha' + \omega_x \dot{\psi} \cos \alpha' - \dot{\omega}_y \cos \alpha' + \omega_y \dot{\psi} \sin \alpha' \tag{A-26}$$

$$\dot{\omega}_{\zeta_p} = \dot{\omega}_z + \ddot{\psi} \tag{A-27}$$

Rotor-Fixed Coordinates

The relationship between the rotor-fixed $\xi_1 - \eta_1 - \zeta_1$ system and the projectile fixed X-Y-Z system is shown in figure A-3 (see also ref 1). The $\xi_1 - \eta_1$ plane is parallel to the X-Y plane and contains the center of mass C_1 of the rotor (referred to as link 1 below). The ξ_1-axis connects the point O_1 on the rotor pivot centerline and point C_1.

The rotor angles ϕ_{1c} and ϕ_1 are measured in the $\xi_1 - \eta_1$ plane. ϕ_{1c} represents the initial position of the ξ_1-axis, i.e. the ξ_{1o} axis, with respect to the x-axis.

The unit vectors associated with the rotor-fixed system are given by:

$$\bar{n}_{\xi_1} = \cos(\phi_{1c} + \phi_1)\bar{i} + \sin(\phi_{1c} + \phi_1)\bar{j} \tag{A-28}$$

$$\bar{n}_{\eta_1} = -\sin(\phi_{1c} + \phi_1)\bar{i} + \cos(\phi_{1c} + \phi_1)\bar{j} \tag{A-29}$$

and

$$\bar{n}_{\zeta_1} = \bar{k} \tag{A-30}$$

Because of the gear train, it is best to let (see ref 1, eq B-123):

$$\phi_1 = N_{31}\ \phi_T \tag{A-31}$$

Then

$$\gamma = \phi_{1c} + N_{31}\ \phi_T \tag{A-32}$$

The absolute angular velocity $\bar{\omega}_{b/a}$ of the projectile is expressed in terms of the rotor fixed coordinates with the help of equations A-1 and A-28 to A-30:

$$\begin{aligned}\bar{\omega}_{b/a} &= \omega_x\bar{i} + \omega_y\bar{j} + \omega_z\bar{k} \\ &= \omega_x(\cos\gamma\ \bar{n}_{\xi_1} - \sin\gamma\ \bar{n}_{\eta_1}) \\ &\quad + \omega_y(\sin\gamma\ \bar{n}_{\xi_1} + \cos\gamma\ \bar{n}_{\eta_1}) + \omega_z\ \bar{n}_{\zeta_1}\end{aligned}$$

or

$$\begin{aligned}\bar{\omega}_{b/a} &= [\omega_x \cos\gamma + \omega_y \sin\gamma]\ \bar{n}_{\xi_1} \\ &\quad + [-\omega_x \sin\gamma + \omega_y \cos\gamma]\ \bar{n}_{\eta_1} \\ &\quad + \omega_z\ \bar{n}_{\zeta_1}\end{aligned} \tag{A-33}$$

To obtain the total angular velocity $\bar{\omega}_{1/a}$ of the rotor, its relative angular velocity $\dot{\phi}_1 = N_{31}\dot{\phi}$ must be added vectorially to equation A-33:

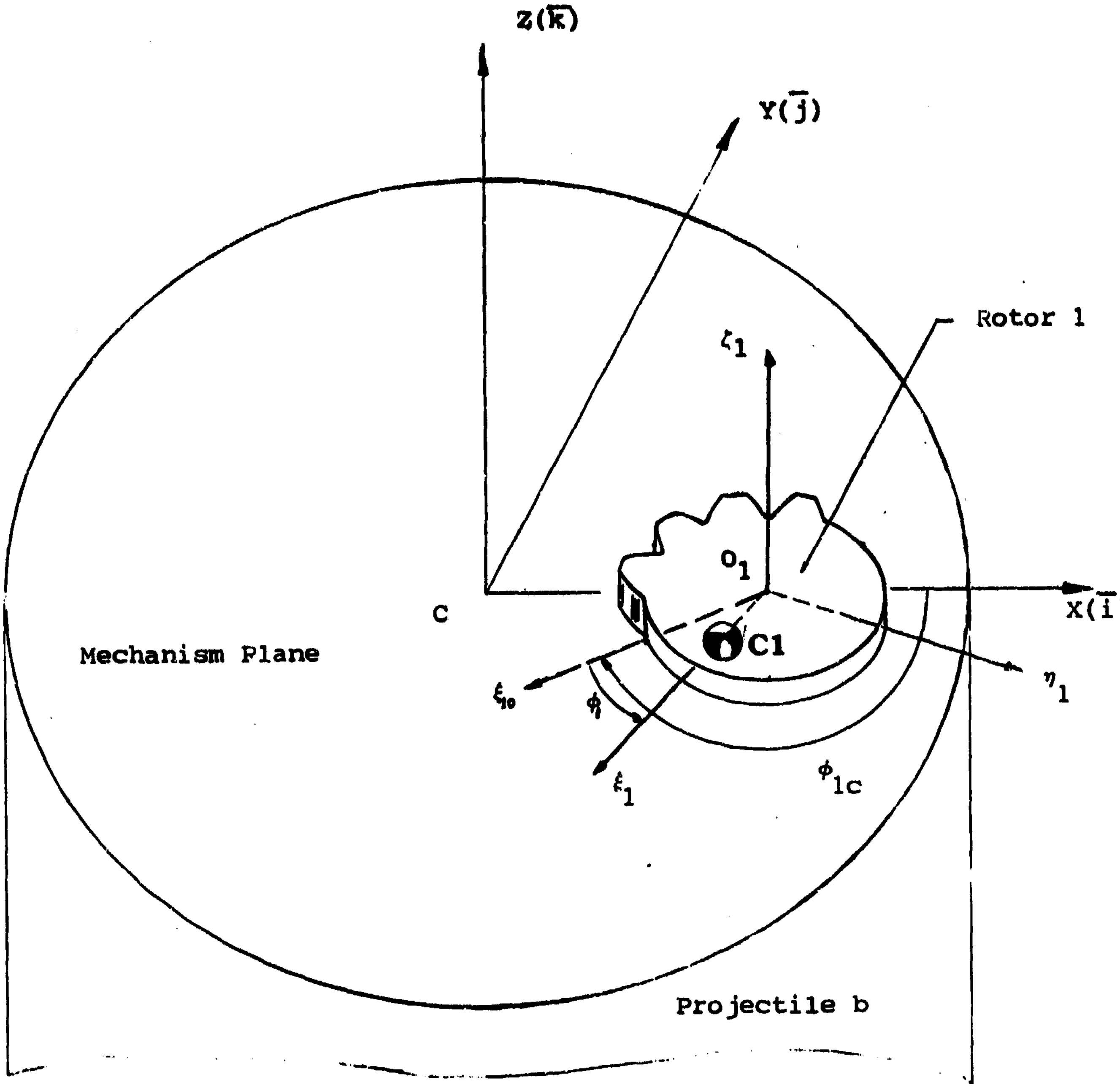

Figure A-3. Rotor-fixed ξ_1-η_1-ζ_1 coordinate system

$$\bar{\omega}_{1/a} = \bar{\omega}_{b/a} + N_{31}\dot{\phi}\ \bar{n}_{\zeta_1} \qquad \text{(A-34)}$$

Then, with equation A-33:

$$\bar{\omega}_{1/a} = \omega_{\xi_1}\ \bar{n}_{\xi_1} + \omega_{\eta_1}\ \bar{n}_{\eta_1} + \omega_{\zeta_1}\ \bar{n}_{\zeta_1} \qquad \text{(A-35)}$$

where

$$\omega_{\xi_1} = \omega_x \cos\gamma + \omega_y \sin\gamma \qquad \text{(A-36)}$$

$$\omega_{\eta_1} = -\ \omega_x \sin\gamma + \omega_y \cos\gamma \qquad \text{(A-37)}$$

$$\omega_{\zeta_1} = \omega_z + N_{31}\ \dot{\phi} \qquad \text{(A-38)}$$

To obtain the absolute angular acceleration $\dot{\bar{\omega}}_{1/a}$ of the rotor, differentiate the measure numbers of equation A-35 with respect to time. Therefore

$$\dot{\bar{\omega}}_{1/a} = \dot{\omega}_{\xi_1}\ \bar{n}_{\xi_1} + \dot{\omega}_{\eta_1}\ \bar{n}_{\eta_1} + \dot{\omega}_{\zeta_1}\ \bar{n}_{\zeta_1} \qquad \text{(A-39)}$$

where

$$\dot{\omega}_{\xi_1} = \dot{\omega}_x \cos\gamma - \omega_x N_{31}\ \dot{\phi} \sin\gamma + \dot{\omega}_y \sin\gamma + \omega_y N_{31}\ \dot{\phi} \cos\gamma \qquad \text{(A-40)}$$

$$\dot{\omega}_{\eta_1} = -\ \dot{\omega}_x \sin\gamma - \omega_x N_{31}\ \dot{\phi} \cos\gamma + \dot{\omega}_y \cos\gamma - \omega_y N_{31}\ \dot{\phi} \sin\gamma \qquad \text{(A-41)}$$

$$\dot{\omega}_{\zeta_1} = \dot{\omega}_z + N_{31}\ \ddot{\phi} \qquad \text{(A-42)}$$

Two Ways of Obtaining Expressions for Absolute Angular Velocities and Accelerations of Components, Such as the Pallet, in Terms of Projectile-Fixed Coordinates

Let it be required to express the absolute angular velocity and the absolute angular acceleration of the pallet, as given by equations A-20 and A-24, in terms of the projectile fixed x'-y'-z' system (fig. A-2). This is accomplished by substitution of equations A-8, A-9, and A-14 for the unit vectors of the above expressions.

This leads to

$$\bar{\omega}_{p/a_{x'y'z'}} = -(\omega_x \cos \beta_3 + \omega_y \sin \beta_3)\bar{i}' + (\omega_x \sin \beta_3 - \omega_y \cos \beta_3)\bar{j}'$$

$$+ (\omega_z + \dot{\psi})\bar{k}' \tag{A-43}$$

and

$$\dot{\bar{\omega}}_{p/a_{x'y'z'}} = [-\dot{\omega}_x \cos \beta_3 - \dot{\omega}_y \sin \beta_3 + \dot{\psi}\,(\omega_x \sin \beta_3 - \omega_y \cos \beta_3)]\bar{i}'$$

$$+ [\dot{\omega}_x \sin \beta_3 - \dot{\omega}_y \cos \beta_3 + \dot{\psi}\,(\omega_x \cos \beta_3 + \omega_y \sin \beta_3)]\bar{j}'$$

$$+ [\dot{\omega}_z + \ddot{\psi}]\bar{k}' \tag{A-44}$$

The same results may be obtained if the vector $\dot{\bar{\psi}}$ is interpreted as a variable vector in the primed system, which is attached to the projectile. First let the absolute angular velocity of the projectile be expressed in terms of the x'-y'-z' system. This is accomplished by substituting equations A-6 and A-7 for the unit vectors $\bar{i}$ and $\bar{j}$ in equation A-1. (The unit vector $\bar{k}$ is also $\bar{k}'$ in the present systems.)

Then

$$\bar{\omega}_{b/a_{x'y'z'}} = -(\omega_x \cos \beta_3 + \omega_y \sin \beta_3)\bar{i}'$$

$$+ (\omega_x \sin \beta_3 - \omega_y \cos \beta_3)\bar{j}' + \omega_z\bar{k}' \tag{A-45}$$

The absolute angular velocity of the pallet becomes, according to equation A-16

$$\bar{\omega}_{p/a_{x'y'z'}} = \dot{\psi}\,\bar{k}' + \bar{\omega}_{b/a_{x'y'z'}} \tag{A-46a}$$

or

$$\bar{\omega}_{p/a_{x'y'z'}} = -(\omega_x \cos \beta_3 + \omega_y \sin \beta_3)\bar{i}' + (\omega_x \sin \beta_3 - \omega_y \cos \beta_3)\bar{j}'$$

$$+ (\omega_z + \dot{\psi})\bar{k}' \tag{A-46b}$$

This is identical to equation A-43.

To obtain the absolute angular acceleration of the pallet, the following expression in which $\dot{\psi}\,\bar{k}'$ is treated as a variable vector in the x'-y'-z' system must be evaluated. Therefore,

$$\dot{\bar{\omega}}_{p/a_{x'y'z'}} = \ddot{\psi}\,\bar{k}' + \bar{\omega}_{b/a_{x'y'z'}} \times \dot{\psi}\,\bar{k}' + \dot{\bar{\omega}}_{b/a_{x'y'z'}} \tag{A-47}$$

where differentiation of equation A-45 yields

$$\dot{\bar{\omega}}_{b/a_{x'y'z'}} = -(\dot{\omega}_x \cos \beta_3 + \dot{\omega}_y \sin \beta_3)\bar{i}' + (\dot{\omega}_x \sin \beta_3 - \dot{\omega}_y \cos \beta_3)\bar{j}' + \dot{\omega}_z \bar{k}' \tag{A-48}$$

Completion of all operations in equation A-47 leads to:

$$\begin{aligned}\dot{\bar{\omega}}_{p/a_{x'y'z'}} = {} & [-\dot{\omega}_x \cos \beta_3 - \dot{\omega}_y \sin \beta_3 + \dot{\psi}(\omega_x \sin \beta_3 - \omega_y \cos \beta_3)]\bar{i}' \\ & + [\dot{\omega}_x \sin \beta_3 - \dot{\omega}_y \cos \beta_3 + \dot{\psi}\,(\omega_x \cos \beta_3 + \omega_y \sin \beta_3)]\bar{j}' \\ & + [\dot{\omega}_z + \ddot{\psi}]\bar{k}'\end{aligned} \tag{A-49}$$

This expression is identical to equation A-44.

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APPENDIX B

ANGULAR MOMENTUM AND ITS DERIVATIVES IN

VARIOUS COORDINATE SYSTEMS

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Angular Momentum

The angular momentum vector $\bar{H}_O$, with respect to a point O, has the general expression:

$$\bar{H}_O = [I_{xx}\omega_x - I_{xy}\omega_y - I_{zx}\omega_z]\bar{i}$$
$$+ [-I_{xy}\omega_x + I_{yy}\omega_y - I_{yz}\omega_z]\bar{j}$$
$$+ [-I_{zx}\omega_x - I_{yz}\omega_y + I_{zz}\omega_z]\bar{k} \qquad \text{(B-1)}$$

The above holds for all types of body-fixed and space-fixed coordinate systems. If principal axes are involved, the products of inertia vanish. Note that the angular velocity component must be absolute.

Derivative of Body-Fixed Angular Momentum Vector: Torque Equation

Body b in general motion is shown in figure B-1. It contains the body fixed X-Y-Z system and its angular momentum may be expressed with the help of equation B-1.

The time derivative of the angular momentum with respect to the inertial X_o-Y_o-Z_o system is obtained from:

$$\dot{\bar{H}}_{O/X_oY_oZ_o} = \frac{d}{dt}(\bar{H}_O)_{XYZ} + \bar{\omega} \times \bar{H}_O \qquad \text{(B-2)}$$

where

$\frac{d}{dt}(\bar{H}_O)_{XYZ}$ = derivative of the measure numbers in equation B-1

and

$$\bar{\omega} \times \bar{H}_O = (\omega_x\bar{i} + \omega_y\bar{j} + \omega_z\bar{k}) \times \bar{H}_O$$

It is to be recalled at this point, that the absolute angular acceleration of body b is given by:

$$\dot{\bar{\omega}} = \dot{\omega}_x\bar{i} + \dot{\omega}_y\bar{j} + \dot{\omega}_z\bar{k} \qquad \text{(B-3)}$$

Both $\bar{\omega}$ and $\dot{\bar{\omega}}$ are now expressed in terms of the body fixed coordinates.

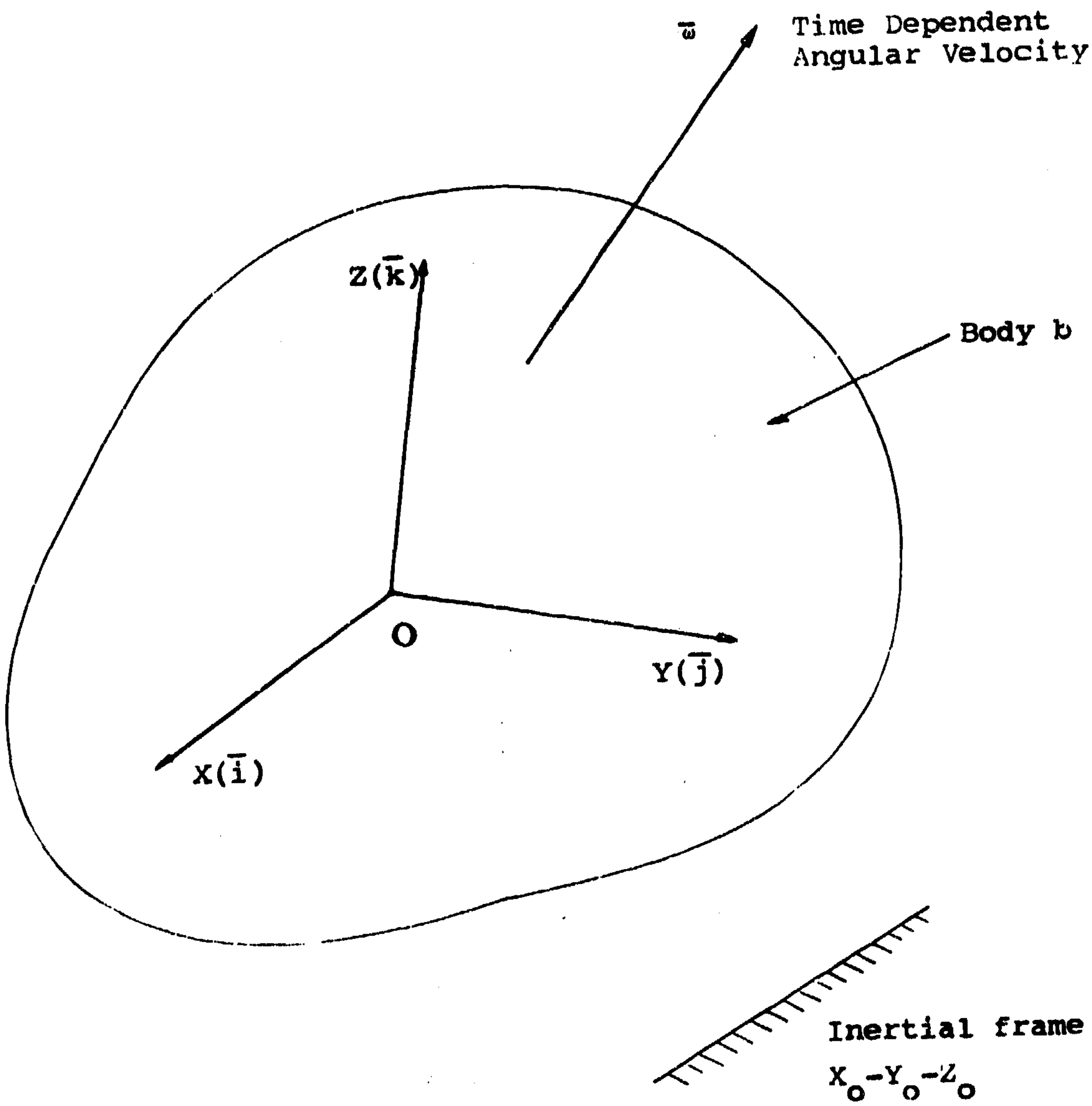

Figure B-1. Body b contains X-Y-Z system

Upon performing all operations of equation B-2, the torque equation with respect to point O results:

$$\bar{M}_O = \dot{\bar{H}}_{O/X_oY_oZ_o} =$$

$$[I_{xx}\dot{\omega}_x + \omega_y\omega_z(I_{zz}-I_{yy}) + I_{xy}\ (\omega_z\omega_x - \dot{\omega}_y)$$

$$- I_{zx}\ (\dot{\omega}_z + \omega_x\omega_y) - I_{yz}\ (\omega_y^{\ 2} - \omega_z^{\ 2})]\bar{i}$$

$$+ [I_{yy}\dot{\omega}_y + \omega_x\omega_z(I_{xx}-I_{zz}) + I_{yz}\ (\omega_x\omega_y - \dot{\omega}_z)$$

$$- I_{xy}(\dot{\omega}_x + \omega_y\omega_z) - I_{zx}\ (\omega_z^{\ 2} - \omega_x^{\ 2})]\bar{j}$$

$$+ [I_{zz}\dot{\omega}_z + \omega_x\omega_y\ (I_{yy}-I_{xx}) + I_{zx}\ (\omega_y\omega_z - \dot{\omega}_x)$$

$$- I_{yz}\ (\dot{\omega}_y + \omega_x\omega_z) - I_{xy}\ (\omega_x^{\ 2} - \omega_y^{\ 2})]\bar{k} \qquad \text{(B-4)}$$

When $I_{xy} = I_{yz} = I_{zx} = 0$, the above expression becomes the well known Euler torque equation.

Derivative of Angular Momentum Vector Which is Described in Terms of the Body-Fixed System of a Carrier: Vector-Torque Equation

The carrier body b which has general rotational motion is shown in figure B-2. Its absolute angular velocity and acceleration are given in terms of the indicated body-fixed system, i.e.

$$\bar{\omega}_{b/a} = \omega_{b/ax}\bar{i} + \omega_{b/ay}\bar{j} + \omega_{b/az}\bar{k} \qquad \text{(B-5)}$$

and

$$\dot{\bar{\omega}}_{b/a} = \dot{\omega}_{b/ax}\bar{i} + \dot{\omega}_{b/ay}\bar{j} + \dot{\omega}_{b/az}\bar{k} \qquad \text{(B-6)}$$

respectively.

The symmetrical body c rotates about an axis parallel to the Z-axis with respect to body b with the relative angular velocity

$$\bar{\omega}_{c/b} = \omega_{c/b}(t)\bar{k} \qquad \text{(B-7)}$$

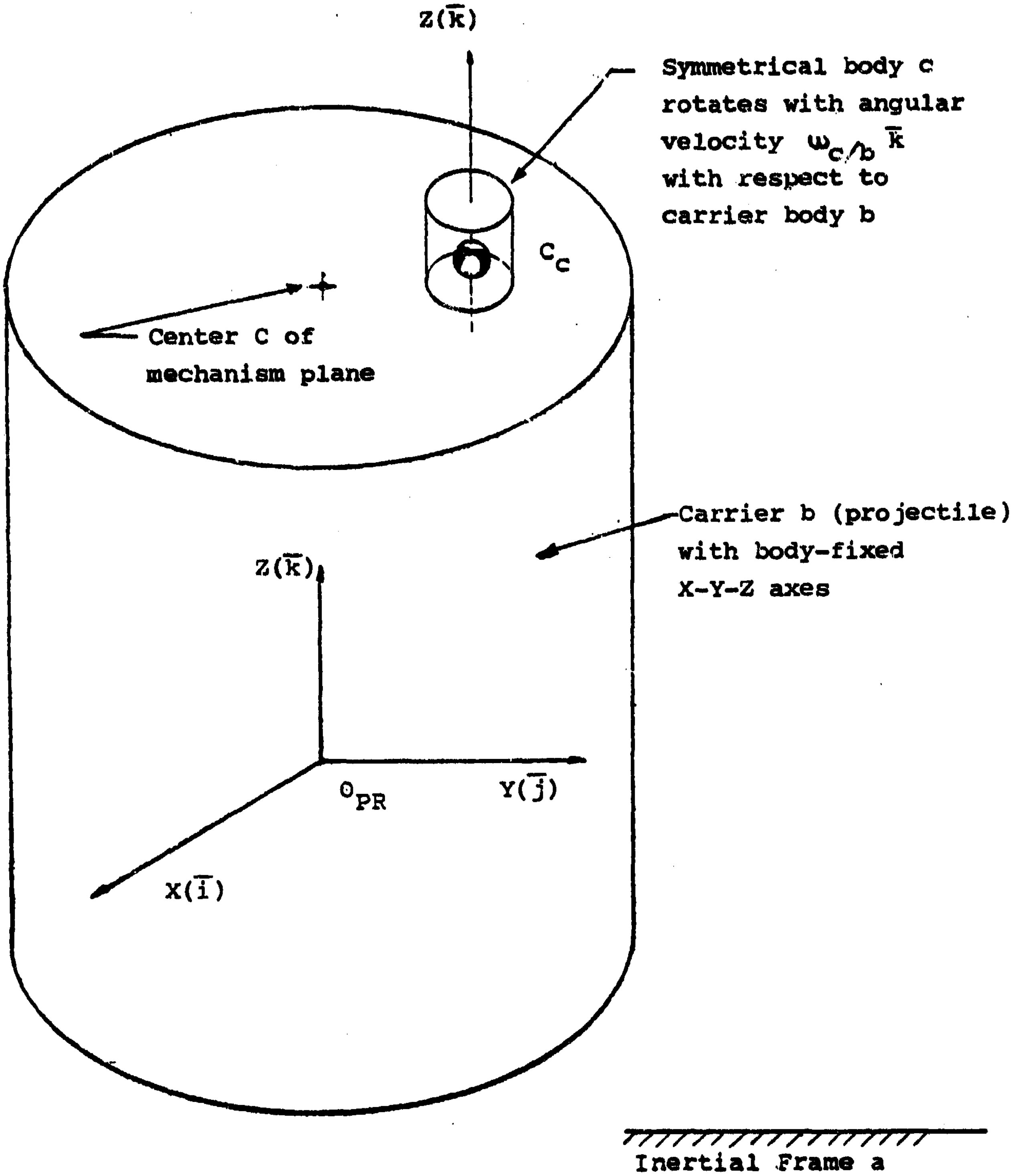

Figure B-2. Symmetrical body c has relative rotation about Z-axis with respect to carrier b

If the absolute angular velocity of the body is expressed in the X-Y-Z system and fixed to the carrier (projectile), the following is obtained:

$$\bar{\omega}_{c/a} = \bar{\omega}_{c/b} + \bar{\omega}_{b/a} \tag{B-8}$$

(For comparison see equation A-46.)

To obtain the absolute angular velocity $\dot{\bar{\omega}}_{c/a}$ in terms of the projectile fixed system, interpret $\bar{\omega}_{c/b}$ as a variable vector in the X-Y-Z system. Then,

$$\dot{\bar{\omega}}_{c/a_{X_oY_oZ_o}} = \dot{\bar{\omega}}_{c/b} + \bar{\omega}_{b/a} \times \bar{\omega}_{c/b} + \dot{\bar{\omega}}_{b/a} \tag{B-9}$$

where

$\dot{\bar{\omega}}_{c/a} = \dot{\omega}_{c/b}\bar{k}$, the relative angular acceleration of component C with respect to projectile b

$\dot{\bar{\omega}}_{b/a}$ = given by equation B-6

Because body c is symmetrical, its products of inertia with respect to its center of mass C_c are zero. This symmetry also makes it possible to express its angular momentum with respect to point C_c in terms of the body-fixed system of the carrier b. (Regardless of the angle of body c with respect to body b, the moments of inertia I_{xx} and I_{yy}, expressed in terms of body b, remain invariant.) The angular momentum vector, with respect to point C_c, appropriately reduced, becomes according to equations B-1 and B-8:

$$\bar{H}_{C_c} = I_{xx}\omega_{b/ax}\bar{i} + I_{yy}\omega_{b/ay}\bar{j} + I_{zz}(\omega_{b/az} + \omega_{c/b})\bar{k} \tag{B-10}$$

The vector $\bar{H}_{C_c}$ must be interpreted as a variable vector in the carrier-fixed coordinate system. Its time derivative with respect to the inertial system is therefore obtained by the following operations:

$$\dot{\bar{H}}_{C_{c/X_oY_oZ_o}} = \frac{d}{dt}(\bar{H}_{C_c})_{XYZ} + \bar{\omega}_{b/a} \times \bar{H}_{C_c} \tag{B-11}$$

When applied to equation B-10, the following is obtained:

$$\dot{\bar{H}}_{C_{c/X_oY_oZ_o}} = I_{xx}\,\dot{\omega}_{b/ax}\bar{i} + I_{yy}\,\dot{\omega}_{b/ay}\bar{j} + I_{zz}\,(\dot{\omega}_{b/az} + \dot{\omega}_{c/b})\bar{k}$$

$$+ (\omega_{b/ax}\bar{i} + \omega_{b/ay}\bar{j} + \omega_{b/az}\bar{k}) \times [I_{xx}\omega_{b/ax}\bar{i} + I_{yy}\,\omega_{b/ay}\bar{j}$$

$$+ I_{zz}(\omega_{b/az} + \omega_{c/b})\bar{k}] \tag{B-12}$$

The above becomes the torque equation with respect to point C_c:

$$\dot{\bar{H}}_{C_{c/X_oY_oZ_o}} = \bar{M}_{C_c} = [I_{xx}\dot{\omega}_{b/ax} + I_{zz}\omega_{b/ay}\,(\omega_{b/az} + \omega_{c/b}) - I_{yy}\omega_{b/ay}\omega_{b/az}]\bar{i}$$

$$+ [I_{yy}\dot{\omega}_{b/ay} + I_{xx}\omega_{b/ax}\omega_{b/az} - I_{zz}\omega_{b/ax}\,(\omega_{b/az} + \omega_{c/b})]\bar{j}$$

$$+ I_{zz}\,(\dot{\omega}_{b/az} + \dot{\omega}_{c/b})\bar{k} \tag{B-13}$$

APPENDIX C

ABSOLUTE ACCELERATION OF GEOMETRIC CENTER C OF THE S&A PLANE

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The relationship between the center of mass C_{PR} of the projectile and the center of the plane, where the S&A mechanism is located, is shown in figure C-1. Note that the origin of the projectile fixed X-Y-Z system lies on the geometric axis of the projectile. This axis is assumed to be parallel to the spin axis of the projectile. The center of mass of the projectile, about which all rotation takes place, lies in the same plane as the origin O_{PR} of the body fixed system. The position vector of point C with respect to the center of mass is given by:

$$\bar{R} = R_x \bar{i} + R_y \bar{j} + R_z \bar{k} \tag{C-1}$$

It is assumed that the deceleration of the center of mass due to drag is only in the Z-direction and that it is given by

$$\bar{A}_{C_{PR}/ground} = \ddot{Z}\,\bar{k} \tag{C-2}$$

The absolute acceleration $\bar{A}_{C/ground}$ of point C, may then be obtained from:

$$\bar{A}_{C/ground} = \bar{A}_{C_{PR}/ground} + \bar{\omega} \times (\bar{\omega} \times \bar{R}) + \dot{\bar{\omega}} \times \bar{R} \tag{C-3}$$

where $\bar{\omega}$ and $\dot{\bar{\omega}}$ are obtained from equations A-1 and A-5, respectively. (For clarity they were designated as $\bar{\omega}_{b/a}$ and $\dot{\bar{\omega}}_{b/a}$ in appendix A.)

When the operations of equation C-3 are carried out and equation C-2 is substituted, the following is obtained:

$$\bar{A}_{C/ground} = G_x \bar{i} + G_y \bar{j} + G_z \bar{k} \tag{C-4}$$

where

$$G_x = (\omega_y R_y + \omega_z R_z)\,\omega_x - (\omega_y^2 + \omega_z^2)\,R_x + (\dot{\omega}_y R_z - \dot{\omega}_z R_y) \tag{C-5}$$

$$G_y = (\omega_x R_x + \omega_z R_z)\,\omega_y - (\omega_x^2 + \omega_z^2)\,R_y + (\dot{\omega}_z R_x - \dot{\omega}_x R_z) \tag{C-6}$$

$$G_z = (\omega_x R_x + \omega_y R_y)\,\omega_z - (\omega_x^2 + \omega_y^2)\,R_z + (\dot{\omega}_x R_y - \dot{\omega}_y R_x) + \ddot{Z} \tag{C-7}$$

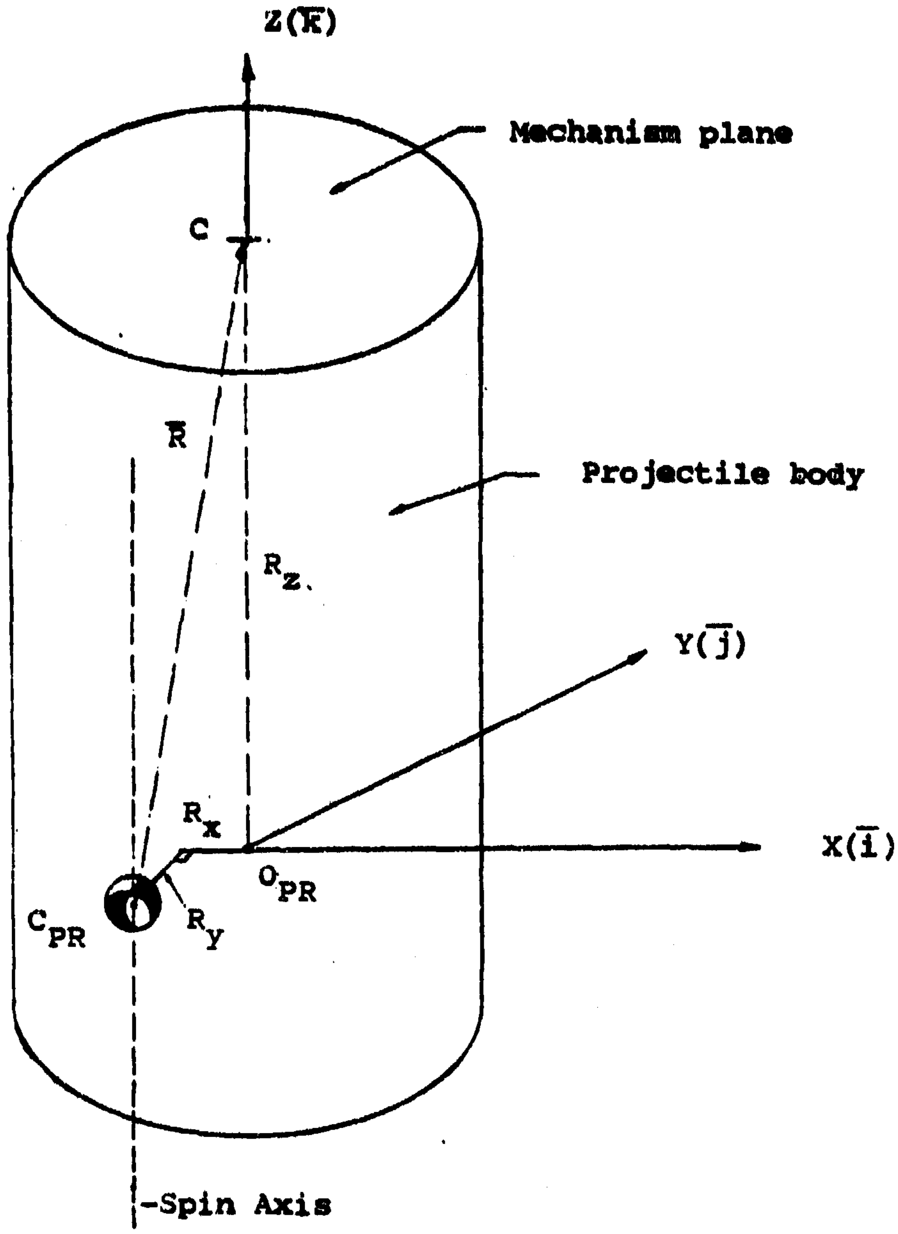

Figure C-1. Relationship between center of mass C_{PR} of projectile and center C of mechanism plane

APPENDIX D

DYNAMICS OF ROTOR-DRIVEN S&A MECHANISM WITH A TWO-PASS INVOLUTE GEAR TRAIN AND A VERGE RUNAWAY ESCAPEMENT OPERATING IN AN AEROBALLISTIC ENVIRONMENT

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Geometry of Fuse Body Configurations

The two possible fuse body configurations of reference 1 are also accommodated in the present simulation. Therefore, all work concerning fuse body angles in this earlier report are also applicable here.

Dynamics of Pallet and Escape Wheel in Coupled Motion

Absoute Acceleration of Pallet Pivot O_p

The position of the pallet pivot O_p with respect to the geometric center C of the mechanism plane is shown in figure D-1. In addition, the relationship of the projectile fixed x'-y'-z' system to the projectile fixed X-Y-Z system is indicated.

The absolute acceleration of point O_p is given by:

$$\bar{A}_{O_p/\text{ground}} = \bar{A}_{O_p/C} + \bar{A}_{C/\text{ground}} \tag{D-1}$$

where, $\bar{A}_{C/\text{ground}}$ is given by equation C-4 of appendix C and

$$\bar{A}_{O_p/C} = \bar{\omega} \times (\bar{\omega} \times \bar{\mathcal{R}}_4) + \dot{\bar{\omega}} \times \bar{\mathcal{R}}_4 \tag{D-2}$$

In the above, $\bar{\omega}$ and $\dot{\bar{\omega}}$ are obtained from equations A-1 and A-5, respectively, and

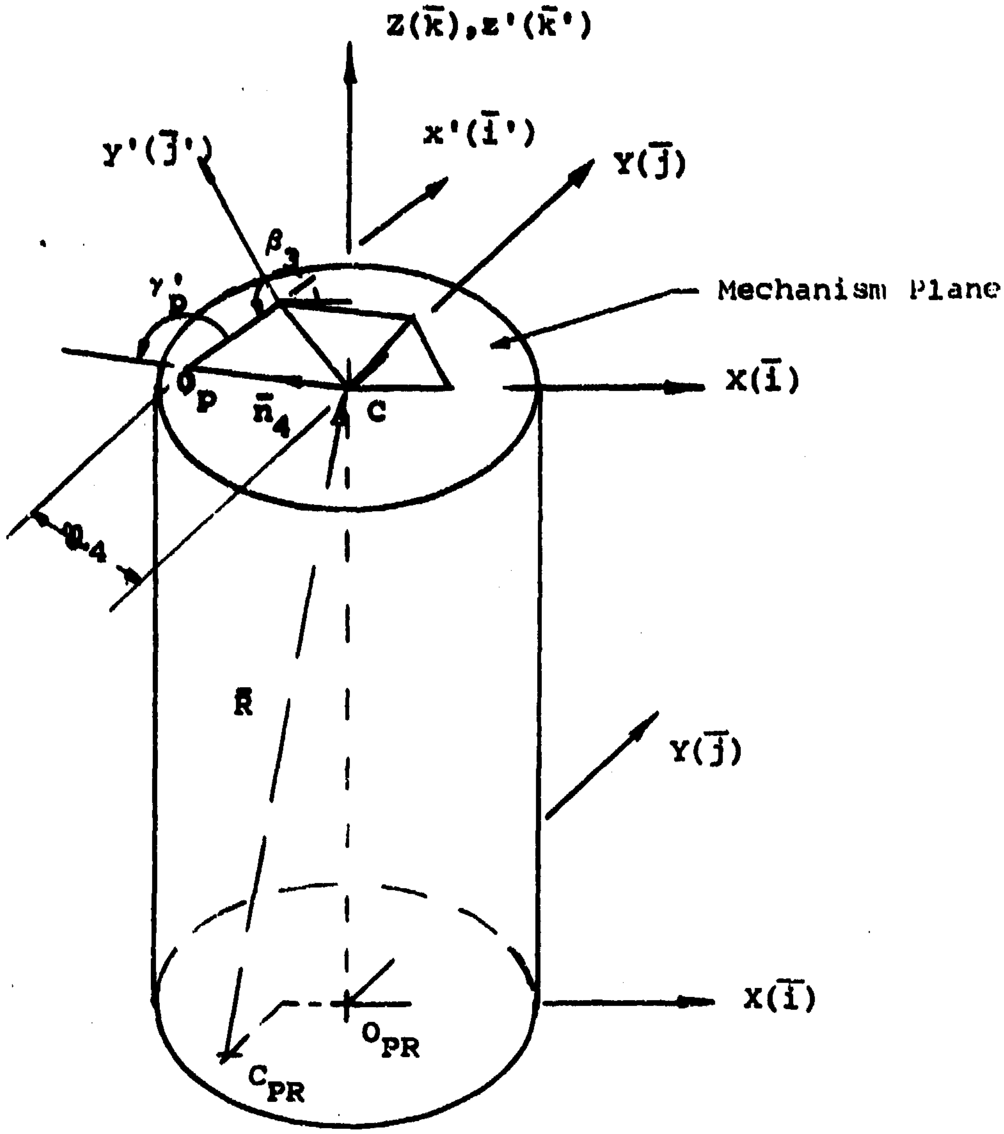
$$\bar{\mathcal{R}}_4 = \mathcal{R}_4 \, \bar{n}_4 \tag{D-3}$$

where, in the primed coordinate system

$$\bar{n}_4 = \cos \gamma_p' \bar{i}' + \sin \gamma_p' \bar{j}' \tag{D-4}$$

After transformation into the X-Y-Z system with the help of equations A-6 and A-7 and some trigonometric rearrangement, the following is obtained:

$$\bar{n}_4 = - \cos (\gamma_p' + \beta_3)\bar{i} - \sin (\gamma_p' + \beta_3)\bar{j} \tag{D-5}$$



C_{PR} = Projectile Center of Mass

C = Geometric Center of Mechanism Plane

Figure D-1. Relationship between mechanism plane-fixed x'-y'-z' and X-Y-Z systems (the mechanism plane is part of projectile)

Equation D-3 may now be written as:

$$\bar{\mathcal{R}}_4 = \mathcal{R}_x\bar{i} + \mathcal{R}_y\bar{j} = -\mathcal{R}_4 \cos\left(\gamma_p' + \beta_3\right)\bar{i} - \mathcal{R}_4 \sin\left(\gamma_p' + \beta_3\right)\bar{j} \tag{D-6}$$

With the above, equation D-2 is now evaluated:

$$\bar{A}_{O_p/C} = H_x\bar{i} + H_y\bar{j} + H_z\bar{k} \tag{D-7}$$

where

$$H_x = \left[\mathcal{R}_{4y}\ \omega_x\ \omega_y - \mathcal{R}_{4x}\ \left(\omega_y^2 + \omega_z^2\right) - \mathcal{R}_{4y}\ \dot{\omega}_z\right] \tag{D-8}$$

$$H_y = \left[\mathcal{R}_{4x}\ \omega_x\ \omega_y - \mathcal{R}_{4y}\ \left(\omega_x^2 + \omega_z^2\right) + \mathcal{R}_{4x}\ \dot{\omega}_z\right] \tag{D-9}$$

$$H_z = \left[\left(\mathcal{R}_{4x}\ \omega_x + \mathcal{R}_{4y}\ \omega_y\right)\ \omega_z + \left(\mathcal{R}_{4y}\ \dot{\omega}_x - \mathcal{R}_{4x}\ \dot{\omega}_y\right)\right] \tag{D-10}$$

The acceleration $\bar{A}_{O_p/\text{ground}}$ is evaluated according to equation D-1 with the help of equations C-4 and D-7, i.e.,

$$\bar{A}_{O_p/\text{ground}} = \left(G_x + H_x\right)\bar{i} + \left(G_y + H_y\right)\bar{j} + \left(G_z + H_z\right)\bar{k} \tag{D-11}$$

For later computational convenience, the above expression is transformed into the x'-y'-z' system:

$$\bar{A}_{O_p/\text{ground}} = K_x\bar{i}' + K_y\bar{j}' + K_z\bar{k}' \tag{D-12}$$

where

$$K_x = -\left(G_x + H_x\right)\cos\beta_3 - \left(G_y + H_y\right)\sin\beta_3 \tag{D-13}$$

$$K_y = \left(G_x + H_x\right)\sin\beta_3 - \left(G_y + H_y\right)\cos\beta_3 \tag{D-14}$$

$$K_z = G_z + H_z \tag{D-15}$$

Acceleration of Pallet Center of Mass C_p with Respect to the Pallet Pivot O_p

When the relative acceleration of the pallet center of mass with respect to the pallet pivot is formulated in terms of the pallet-fixed $\xi_p - \eta_p - \zeta_p$ coordinate system, the following is obtained (fig. D-2):

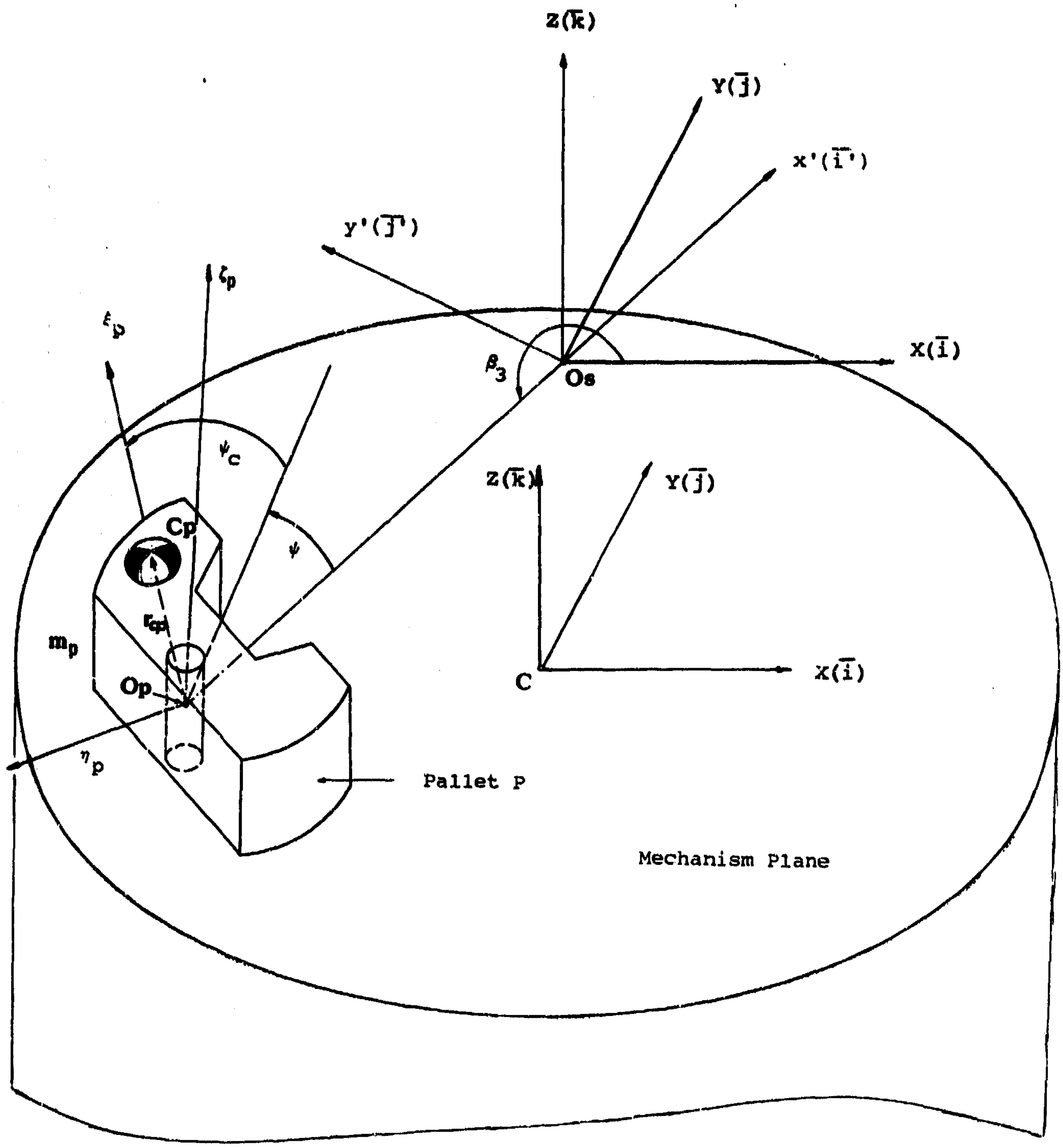


Figure D-2. Pallet center of mass C_p and pallet pivot O_p

$$\bar{A}_{C_p/O_p} = \bar{\omega}_{p/a} \times (\bar{\omega}_{p/a} \times r_{cp}\bar{n}_{\xi_p}) + \dot{\bar{\omega}}_{p/a} \times r_{cp}\bar{n}_{\xi_p} \tag{D-16}$$

where

$$\bar{\omega}_{p/a} = \omega_{\xi_p}\bar{n}_{\xi_p} + \omega_{\eta_p}\bar{n}_{\eta_p} + \omega_{\zeta_p}\bar{n}_{\zeta_p}$$

$$\dot{\bar{\omega}}_{p/a} = \dot{\omega}_{\xi_p}\bar{n}_{\xi_p} + \dot{\omega}_{\eta_p}\bar{n}_{\eta_p} + \dot{\omega}_{\zeta_p}\bar{n}_{\zeta_p}$$

$$r_{cp} = O_p - C_p$$

Appropriate substitution and evaluation of equation D-16 furnishes:

$$\begin{aligned}\bar{A}_{C_p/O_p} = r_{c_p} \{ & [-(\omega_x \sin\alpha' - \omega_y \cos\alpha')^2 - (\omega_z + \dot{\psi})^2]\,\bar{n}_{\xi_p} \\ & + [\sin\alpha' \cos\alpha' (\omega_y^2 - \omega_x^2) + \omega_x\omega_y (\cos^2\alpha' - \sin^2\alpha') \\ & \quad + \dot{\omega}_z + \ddot{\psi}]\,\bar{n}_{\eta_p} \\ & + [-\sin\alpha' (\dot{\omega}_x + 2\omega_y \dot{\psi} + \omega_y\omega_z) + \cos\alpha' (\dot{\omega}_y \\ & \quad - 2\omega_x \dot{\psi} - \omega_x\omega_z)]\,\bar{n}_{\zeta_p} \}\end{aligned} \tag{D-17}$$

The above expression is now transformed into the x'-y'-z' system (again for later computational convenience) with the help of equations A-8, A-9, and A-14:

$$\bar{A}_{C_p/O_p} = T_x\,\bar{i}' + T_y\,\bar{j}' + T_z\,\bar{k}' \tag{D-18a}$$

where

$$\begin{aligned}T_x = r_{cp}[&-\omega_x^2 \sin\beta_3 \sin\alpha' - \omega_y^2 \cos\beta_3 \cos\alpha' \\ & + \omega_x\omega_y \sin(\alpha' + \beta_3) - (\omega_z + \dot{\psi})^2 \cos\beta - (\dot{\omega}_z + \ddot{\psi}) \sin\beta]\end{aligned} \tag{D-18b}$$

$$T_y = r_{cp}\left[-\omega_x^2 \cos\beta_3 \sin\alpha' + \omega_y^2 \sin\beta_3 \cos\alpha'\right.$$

$$\left. + \omega_x\omega_y \cos\left(\alpha' + \beta_3\right) - (\omega_z + \dot{\psi})^2 \sin\beta + \left(\dot{\omega}_z + \ddot{\psi}\right)\cos\beta\right] \quad \text{(D-18c)}$$

$$T_z = r_{cp}\left[-\sin\alpha' \left(\dot{\omega}_x + 2\,\omega_y\,\dot{\psi} + \omega_y\omega_z\right)\right.$$

$$\left. + \cos\alpha' \left(\dot{\omega}_y - 2\,\omega_x\,\dot{\psi} - \omega_x\omega_z\right)\right] \quad \text{(D-18d)}$$

Absolute Acceleration of Pallet Center of Mass C_p

The total acceleration of the pallet center of mass is given by:

$$\bar{A}_{C_p/\text{ground}} = \bar{A}_{C_p/O_p} + \bar{A}_{O_p/\text{ground}} \quad \text{(D-19)}$$

Substitution of equations D-12 and D-18a into the above yields the following expression:

$$\bar{A}_{C_p/\text{ground}} =$$

$$\left\{r_{cp}\left[-\omega_x^2 \sin\beta_3 \sin\alpha' - \omega_y^2 \cos\beta_3 \cos\alpha' + \omega_x\omega_y \sin\left(\alpha' + \beta_3\right)\right.\right.$$

$$\left.\left. - \left(\omega_z + \dot{\psi}\right)^2 \cos\beta - \left(\dot{\omega}_z + \ddot{\psi}\right)\sin\beta\right] + K_x\right\}\bar{i}'$$

$$+ \left\{r_{cp}\left[-\omega_x^2 \cos\beta_3 \sin\alpha' + \omega_y^2 \sin\beta_3 \cos\alpha' - \omega_x\omega_y \cos\left(\alpha' + \beta_3\right)\right.\right.$$

$$\left.\left. - \left(\omega_z + \dot{\psi}\right)^2 \sin\beta + \left(\dot{\omega}_z + \ddot{\psi}\right)\cos\beta\right] + K_y\right\}\bar{j}'$$

$$+ \left\{r_{cp}\left[-\left(\dot{\omega}_x + \omega_y\omega_z\right)\sin\alpha' + \left(\dot{\omega}_y - \omega_x\omega_z\right)\cos\alpha'\right.\right.$$

$$\left.\left. - 2\,\dot{\psi}\left(\omega_x \cos\alpha' + \omega_y \sin\alpha'\right)\right] + K_z\right\}\bar{k}' \quad \text{(D-20)}$$

Signum Functions

Before deriving the equations of motion of the pallet and the escape wheel, it is necessary to introduce two signum functions which will be used to determine the directions of the friction forces at the pallet-escape wheel interface and at the pallet pivots, respectively (ref 1).

The relationship between the contact point S on the escape wheel and the coincident point T on the pallet is shown in figure D-3a. The signum function s_4 makes use of the relative velocity $V_{S/T}$; i.e.

$$s_4 = \frac{V_{S/T}}{|V_{S/T}|} \tag{D-21}$$

The signum function s_5, which is associated with pallet rotation, is defined by:

$$s_5 = \frac{\dot{\psi}}{|\dot{\psi}|} \tag{D-22}$$

Pallet and Escape Wheel in Entrance Coupled Motion

A free body diagram of the pallet with the normal force F_n and the friction force μF_n acting on its entrance working surface is shown in figure D-3a. The normal and friction forces acting on the upper and lower pivots of the pallet are shown in figure D-3b. For verge nomenclature see reference 1.

Force Equations for Pallet. The force equations for the pallet in entrance coupled motion are obtained from Newton's law according to

$$\Sigma \bar{F} = m_p \bar{A}_{C_p/\text{ground}} \tag{D-23}$$

where the acceleration $\bar{A}_{C_p/\text{ground}}$ of the pallet center of mass is given by equation D-20. The sum of the forces is obtained with the help of the figures mentioned. (For escapement forces, see equation E-43 of reference 1.) Equation D-23 becomes:

$$F_n \bar{n}_n + \mu_1 s_4 F_n \bar{n}_t + F_{z'} \bar{k}' - F_{xu'} \bar{i}'$$

$$- F_{y'u} \bar{j}' - \mu_1 s_5 F_{x'u} \bar{j}' + s_5 \mu_1 F_{y'u} \bar{i}'$$

$$+ F_{x'L} \bar{i}' + F_{y'L} \bar{j}' + \mu_1 s_5 F_{x'L} \bar{j}' - \mu_1 s_5 F_{y'L} \bar{i}'$$

$$= m_p \Big[\Big\{ r_{cp} \big[- \omega_x^2 \sin \beta_3 \sin \alpha' - \omega_y^2 \cos \beta_3 \cos \alpha'$$

$$+ \omega_x \omega_y \sin (\alpha' + \beta_3) - (\omega_z + \dot{\psi})^2 \cos \beta - (\dot{\omega}_z + \ddot{\psi}) \sin \beta \big] + K_x \Big\} \bar{i}'$$

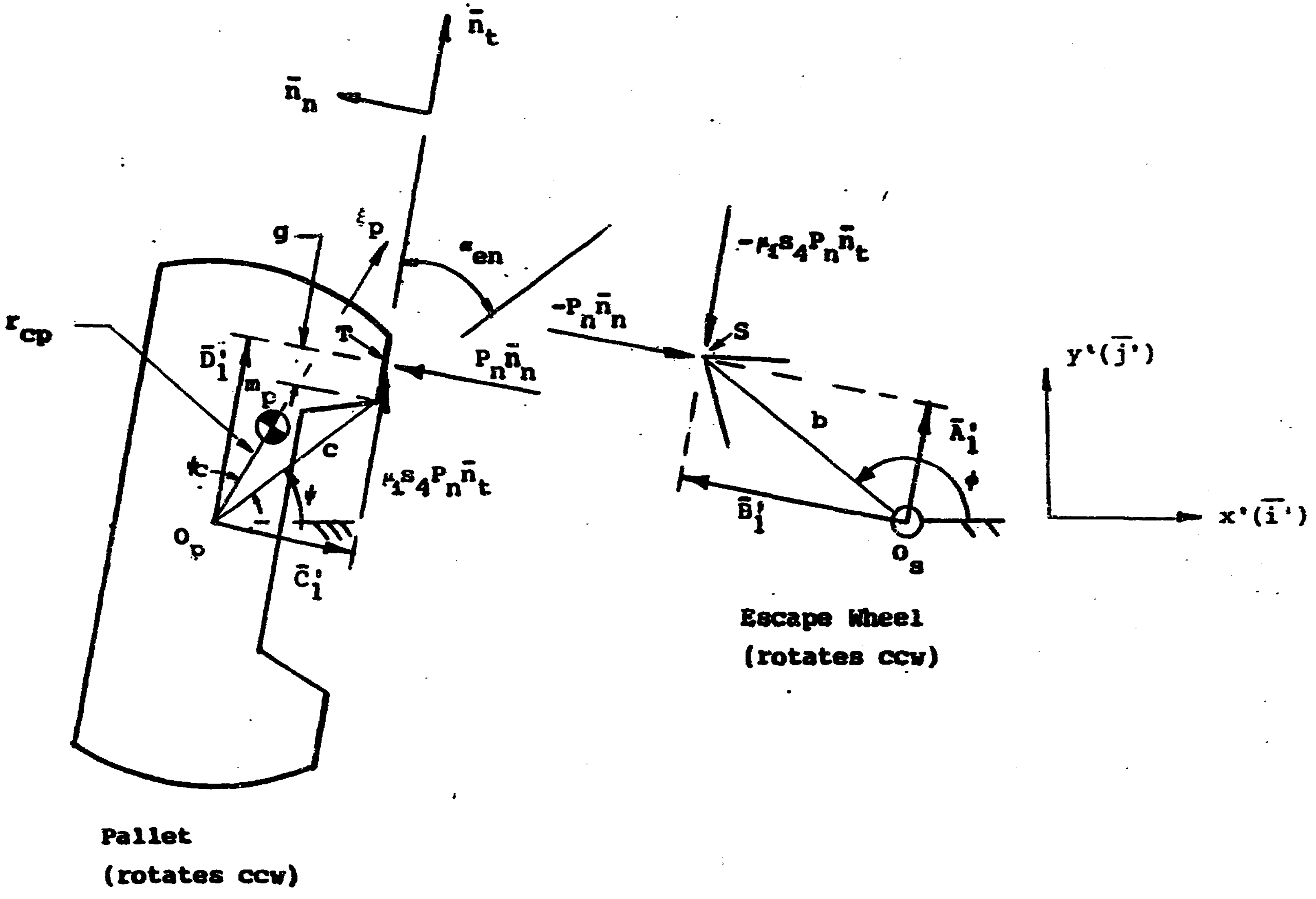


Figure D-3a. Top view free body diagram of pallet in entrance coupled motion

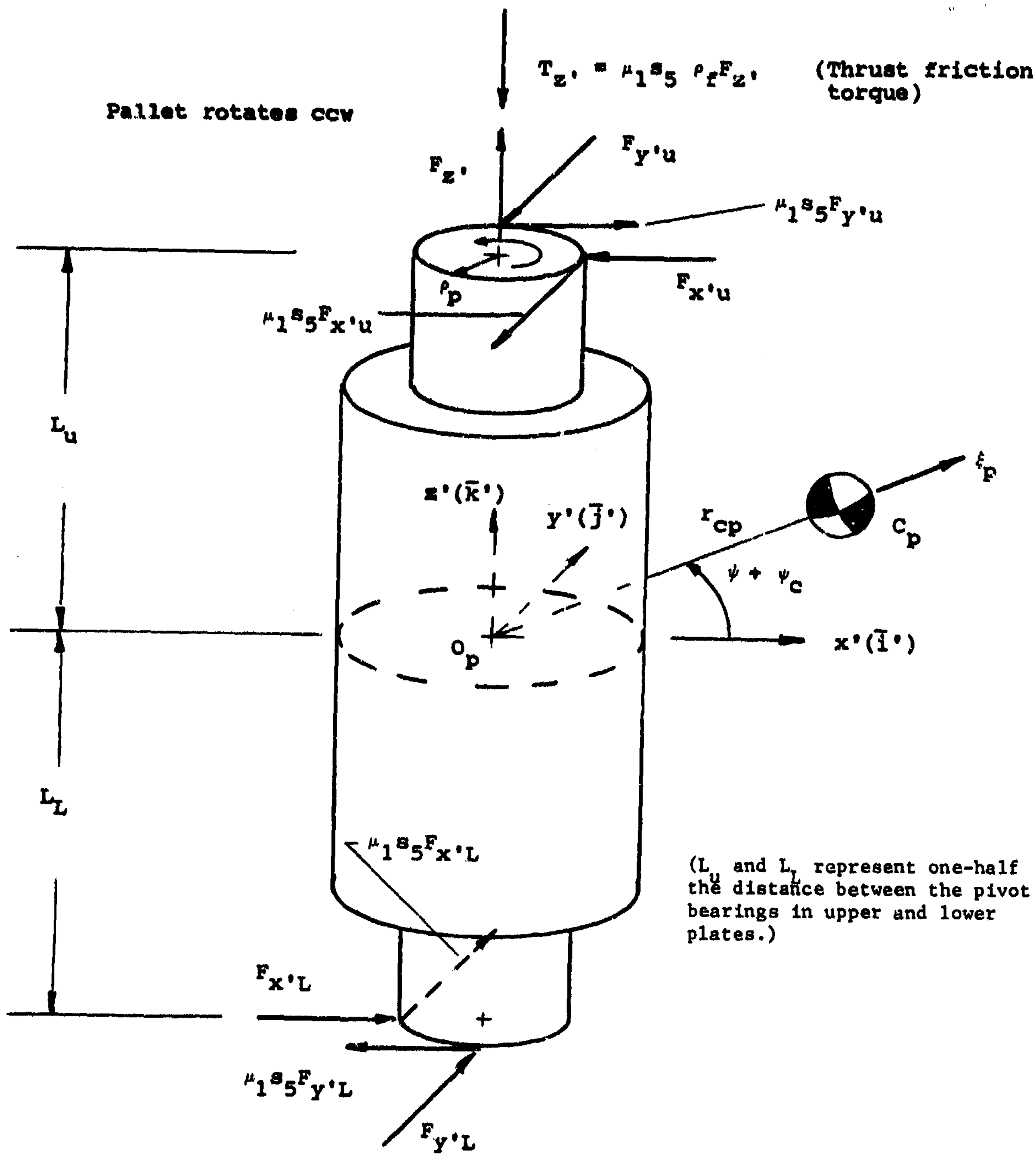


Figure D-3b. Pallet in entrance coupled motion. Normal forces, friction forces, and thrust friction torque acting on pallet pivots.

$$+ \left\{ r_{cp} \left[- \omega_x^2 \cos \beta_3 \sin \alpha' + \omega_y^2 \sin \beta_3 \cos \alpha' - \omega_x \omega_y \cos (\alpha' + \beta_3) \right. \right.$$

$$\left. \left. - (\omega_z + \dot{\psi})^2 \sin \beta + (\dot{\omega}_z + \ddot{\psi}) \cos \beta \right] + K_y \right\} \bar{j}'$$

$$+ \left\{ r_{cp} \left[- (\dot{\omega}_x + \omega_y \omega_z) \sin \alpha' + (\dot{\omega}_y - \omega_x \omega_z) \cos \alpha' \right. \right.$$

$$\left. \left. - 2 \mathring{\psi}_p (\omega_x \cos \alpha' + \omega_y \sin \alpha') \right] + K_z \right\} \bar{k}' \Big] \qquad \text{(D-24)}$$

where

$F_{x'u}$ and $F_{y'u}$ are the normal force components acting on the upper pivot

$F_{x'L}$ and $F_{y'L}$ act on the lower pivot

$F_{z'}$ represents a thrustforce exerted on the pivot shaft

Note that, as in reference 1, the force and moment equations of the pallet are given in the x'-y'-z' system for computational convenience.

The unit vectors $\bar{n}_t$ and $\bar{n}_n$ are expressed according to equations B-5 and B-6 of reference 1 in the primed system as follows:

$$\bar{n}_t = \cos (\psi + \alpha) \bar{i}' + \sin (\psi + \alpha) \bar{j}' \qquad \text{(D-25)}$$

$$\bar{n}_n = - \sin (\psi + \alpha) \bar{i}' + \cos (\psi + \alpha) \bar{j}' \qquad \text{(D-26)}$$

The angle α is associated with the pallet and is different for entrance and exit contact.

Substitution of equations D-25 and D-26 into equation D-24 furnishes the following component expressions:

<u>x' - component of force equation</u>

$$- P_n \sin (\psi + \alpha) + \mu_1 s_4 P_n \cos (\psi + \alpha) - F_{x'u} + \mu_1 s_5 F_{y'u}$$

$$+ F_{x'L} - \mu_1 s_5 F_{y'L} = m_p \left\{ r_{cp} \left[- \omega_x^2 \sin \beta_3 \sin \alpha' \right. \right.$$

$$- \omega_y^2 \cos \beta_3 \cos \alpha' + \omega_x \omega_y \sin (\alpha' + \beta_3) - (\omega_z + \dot{\psi})^2 \cos \beta$$

$$\left. \left. - (\dot{\omega}_z + \ddot{\psi}) \sin \beta \right] + K_x \right\} \qquad \text{(D-27)}$$

y' - component of force equation

$$P_n \cos(\psi + \alpha) + \mu_1 s_4 P_n \sin(\psi + \alpha) - F_{y'u} - \mu_1 s_5 F_{x'u}$$

$$+ F_{y'L} + \mu_1 s_5 F_{x'L} = m_p\{r_{cp}[- \omega_x^2 \cos\beta_3 \sin\alpha' + \omega_y^2 \sin\beta_3 \cos\alpha'$$

$$- \omega_x\omega_y \cos(\alpha' + \beta_3) - (\omega_z + \dot{\psi}_p)^2 \sin\beta + (\dot{\omega}_z + \ddot{\psi}) \cos\beta]$$

$$+ K_y\} \qquad \text{(D-28)}$$

z' - component of force equation

$$F_{z'} = m_p \{r_{cp}[- (\dot{\omega}_x + \omega_y\omega_z) \sin\alpha' + (\dot{\omega}_y - \omega_x\omega_z) \cos\alpha'$$

$$- 2 \dot{\psi} (\omega_x \cos\alpha' + \omega_y \sin\alpha')] + K_z\} \qquad \text{(D-29)}$$

Moment Equation for the Pallet. The moment equation for the pallet must be written with respect to the accelerated pivot point O_p:

$$\bar{M}_{O_p} = - \bar{A}_{O_p/\text{ground}} \times m_p r_{cp} (\cos\beta\bar{i}' + \sin\beta\bar{j}') + \dot{\bar{H}}_{O_p x'y'z'} \qquad \text{(D-30)}$$

where

$\bar{M}_{O_p}$ = sum of external moments about point O_p. It is assumed that O_p lies in the plane of the center of mass of the verge (normal to the verge pivot axis). It is also assumed that the forces $\bar{P}_n$ and $\mu_1 s_4 P_n$ lie in this plane.

$\bar{A}_{O_p/\text{ground}}$ = absolute acceleration of point O_p according to equation D-12

$\dot{\bar{H}}_{O_p x'y'z'}$ = the rate of change of the angular momentum of the verge with respect to point O_p. This expression is obtained by adapting equation B-4 to the parameters of the pallet and transforming the result into the x'y'z' system.

Determination of $\bar{M}_{O_p}$

The moments due to the verge contact force $\bar{P}_n$ and the associated friction force $\overline{\mu_1 s_4 P_n}$ are taken from equations E-48 of reference 1. The moments due to the pivot forces, both normal and frictional, are obtained with the help of

the figure D-3b. The symbols ρ_p and ρ_f stand for the pallet pivot radius and the pallet thrust friction radius, respectively.* Therefore,

$$\bar{M}_{O_p} = D_1' F_n \bar{k}' - \mu_1 s_4 C_1' F_n \bar{k}' - \mu_1 s_5 \rho_f F_{z'} \bar{k}'$$

$$+ (L_u \bar{k}' + \rho_p \bar{j}') \times (- F_{y'u} \bar{j}' + \mu_1 s_5 F_{y'u} \bar{i}')$$

$$+ (L_u \bar{k}' + \rho_p \bar{i}') \times (- F_{x'u} \bar{i}' - \mu_1 s_5 F_{x'u} \bar{j}')$$

$$+ (- L_L \bar{k}' - \rho_p \bar{j}') \times (F_{y'L} \bar{j}' - \mu_1 s_5 F_{y'L} \bar{i}')$$

$$+ (- L_L \bar{k}' - \rho_p \bar{i}') \times (F_{x'L} \bar{i}' + \mu_1 s_5 F_{x'L} \bar{j}') \qquad \text{(D-31)}$$

The above becomes:

$$\bar{M}_{O_p} = [L_u F_{y'u} + L_u \mu_1 s_5 F_{x'u} + L_L F_{y'L} + L_L \mu_1 s_5 F_{x'L}]\bar{i}'$$

$$+ [L_u \mu_1 s_5 F_{y'u} - L_u F_{x'u} + L_L \mu_1 s_5 F_{y'L} - L_L F_{x'L}]\bar{j}'$$

$$+ [F_n (D_1' - \mu_1 s_4 C_1') - \mu_1 \rho_f s_5 F_{z'} - \rho_p \mu_1 s_5 F_{y'u}$$

$$- \rho_p \mu_1 s_5 F_{x'u} - \rho_p \mu_1 s_5 F_{y'L} - \rho_p \mu_1 s_5 F_{x'L}]\bar{k}' \qquad \text{(D-32)}$$

<u>Determination of $- \bar{A}_{O_p/\text{ground}} \times m_p r_{cp} (\cos \beta \, \bar{i}' + \sin \beta \, \bar{j}')$</u>

With the help of equation D-12, for the above cross-product the following is obtained:

$$- (K_x \bar{i}' + K_y \bar{j}' + K_z \bar{k}') \times m_p r_{cp} (\cos \beta \, \bar{i}' + \sin \beta \, \bar{j}')$$

$$= m_p r_{cp} K_z \sin \beta \, \bar{i}' - m_p r_{cp} K_z \cos \beta \, \bar{j}' - m_p r_{cp} (K_x \sin \beta - K_y \cos \beta)\bar{k}' \qquad \text{(D-33)}$$

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* Reference 8 for determination of thrust friction radius, p 268.

Determination of $\dot{\bar{H}}_{O_p x'y'z'}$

As stated earlier, equation B-4 must first be adapted to the pallet fixed coordinate system with pallet related nomenclature. This leads to:

$$\begin{aligned}
\dot{\bar{H}}_{O_p} = & [I_{\xi\xi_p} \dot{\omega}_\xi + \omega_\eta\omega_\zeta (I_{\zeta\zeta_p} - I_{\eta\eta_p}) + I_{\xi\eta_p} (\omega_\zeta\omega_\xi - \dot{\omega}_\eta) \\
& + I_{\zeta\xi_p} (\dot{\omega}_\zeta + \omega_\xi\omega_\eta) + I_{\eta\zeta} (\omega_\eta^2 - \omega_\zeta^2)]\bar{n}_{\xi_p} \\
& + [I_{\eta\eta_p} \dot{\omega}_\eta + \omega_\xi\omega_\zeta (I_{\xi\xi_p} - I_{\zeta\zeta_p}) + I_{\eta\zeta_p} (\omega_\xi\omega_\eta - \dot{\omega}_\zeta) \\
& - I_{\xi\eta_p} (\dot{\omega}_\xi + \omega_\eta\omega_\zeta) - I_{\zeta\xi} (\omega_\zeta^2 - \omega_\xi^2)]\bar{n}_{\eta_p} \\
& + [I_{\zeta\zeta_p} \dot{\omega}_\zeta + \omega_\xi\omega_\eta (I_{\eta\eta_p} - I_{\xi\xi_p}) + I_{\zeta\xi_p} (\omega_\eta\omega_\zeta - \dot{\omega}_\xi) \\
& - I_{\eta\zeta_p} (\dot{\omega}_\eta + \omega_\xi\omega_\zeta) - I_{\xi\eta_p} (\omega_\xi^2 - \omega_\eta^2)]\bar{n}_{\zeta_p}
\end{aligned} \tag{D-34}$$

The angular velocities and accelerations of the pallet are now expressed according to equations A-21 to A-23 and equations A-25 to A-27, respectively. Subsequently, the unit vectors $\bar{n}_\xi$, $\bar{n}_\eta$, and $\bar{n}_\zeta$ are substituted according to equations A-8, A-9, and A-14.

These operations result in the following component expressions for $\dot{\bar{H}}_{O_p x'y'z'}$:

$$\dot{\bar{H}}_{O_p x'} = A_1 + A_2 \dot{\psi} + A_3 \dot{\psi}^2 + A_4 \ddot{\psi} \tag{D-35}$$

$$\dot{\bar{H}}_{O_p y'} = A_5 + A_6 \dot{\psi} + A_7 \dot{\psi}^2 + A_8 \ddot{\psi} \tag{D-36}$$

$$\dot{\bar{H}}_{O_p z'} = A_9 + A_{10} \ddot{\psi} \tag{D-37}$$

where

$$\begin{aligned}
A_1 = \cos\beta \{ & - I_{\xi\xi_p} (\dot{\omega}_x \cos\alpha' + \dot{\omega}_y \sin\alpha') \\
& + (I_{\zeta\zeta_p} - I_{\eta\eta_p}) \omega_z (\omega_x \sin\alpha' - \omega_y \cos\alpha') \\
& - I_{\xi\eta_p} [\omega_z (\omega_x \cos\alpha' + \omega_y \sin\alpha') + (\dot{\omega}_x \sin\alpha' - \dot{\omega}_y \cos\alpha')
\end{aligned}$$

$$+ I_{\zeta\xi_p}[(\omega_x \cos\alpha' + \omega_y \sin\alpha')(\omega_x \sin\alpha' - \omega_y \cos\alpha') - \dot{\omega}_z]$$

$$- I_{\eta\zeta_p}\ [(\omega_x \sin\alpha' - \omega_y \cos\alpha')^2 - \omega_z^{\ 2}]\}$$

$$- \sin\beta\ \{I_{\eta\eta_p}\ [\dot{\omega}_x \sin\alpha' - \dot{\omega}_y \cos\alpha']$$

$$- (I_{\xi\xi_p} - I_{\zeta\zeta_p})\ \omega_z\ (\omega_x \cos\alpha' + \omega_y \sin\alpha')$$

$$- I_{\eta\zeta_p}[(\omega_x \cos\alpha' + \omega_y \sin\alpha')(\omega_x \sin\alpha' - \omega_y \cos\alpha') + \dot{\omega}_z]$$

$$+ I_{\xi\eta_p}[(\dot{\omega}_x \cos\alpha' + \dot{\omega}_y \sin\alpha') - \omega_z(\omega_x \sin\alpha' - \omega_y \cos\alpha')]$$

$$- I_{\zeta\xi_p}\ [\omega_z^{\ 2} - (\omega_x \cos\alpha' + \omega_y \sin\alpha')^2]\} \qquad \text{(D-38)}$$

$$A_2 = (\omega_x \sin\alpha' - \omega_y \cos\alpha')[(I_{\xi\xi_p} + I_{\zeta\zeta_p} - I_{\eta\eta_p})\cos\beta + 2\ I_{\xi\eta_p} \sin\beta]$$

$$- (\omega_x \cos\alpha' + \omega_y \sin\alpha')\ [2\ I_{\xi\eta_p} \cos\beta + (I_{\eta\eta_p} - I_{\xi\xi_p} + I_{\zeta\zeta_p}) \sin\beta]$$

$$+ 2\ \omega_z\ (I_{\eta\zeta_p} \cos\beta + I_{\zeta\xi_p} \sin\beta) \qquad \text{(D-39)}$$

$$A_3 = I_{\eta\zeta_p} \cos\beta + I_{\zeta\xi_p} \sin\beta \qquad \text{(D-40)}$$

$$A_4 = I_{\eta\zeta_p} \sin\beta - I_{\zeta\xi_p} \cos\beta \qquad \text{(D-41)}$$

$$A_5 = \sin\beta\ \{- I_{\xi\xi_p}\ (\dot{\omega}_x \cos\alpha' + \dot{\omega}_y \sin\alpha')$$

$$+ [I_{\zeta\zeta_p} - I_{\eta\eta_p}]\ \omega_z\ (\omega_x \sin\alpha' - \omega_y \cos\alpha')$$

$$+ I_{\xi\eta_p}[-\omega_z(\omega_x \cos\alpha' + \omega_y \sin\alpha') - (\dot{\omega}_x \sin\alpha' - \dot{\omega}_y \cos\alpha')]$$

$$- I_{\zeta\xi_p}[-(\omega_x \cos\alpha' + \omega_y \sin\alpha')(\omega_x \sin\alpha' - \omega_y \cos\alpha') + \dot{\omega}_z]$$

$$- I_{\eta\zeta_p} [(\omega_x \sin \alpha' - \omega_y \cos \alpha')^2 - \omega_z^2]\}$$

$$+ \cos \beta \{ I_{\eta\eta_p} (\dot{\omega}_x \sin \alpha' - \dot{\omega}_y \cos \alpha')$$

$$- [I_{\xi\xi_p} - I_{\zeta\zeta_p}] \omega_z (\omega_x \cos \alpha' + \omega_y \sin \alpha')$$

$$+ I_{\eta\zeta_p} [-(\omega_x \cos \alpha' + \omega_y \sin \alpha')(\omega_x \sin \alpha' - \omega_y \cos \alpha') - \dot{\omega}_z]$$

$$- I_{\xi\eta_p} [-(\dot{\omega}_x \cos \alpha' + \dot{\omega}_y \sin \alpha') + \omega_z (\omega_x \sin \alpha' - \omega_y \cos \alpha')]$$

$$- I_{\zeta\xi_p} [\omega_z^2 - (\omega_x \cos \alpha' + \omega_y \sin \alpha')^2]\} \qquad \text{(D-42)}$$

$$A_6 = (\omega_x \sin \alpha' - \omega_y \cos \alpha')[(I_{\xi\xi_p} + I_{\zeta\zeta_p} - I_{\eta\eta_p}) \sin \beta - 2 I_{\xi\eta_p} \cos \beta]$$

$$+ (\omega_x \cos \alpha' + \omega_y \sin \alpha')[(I_{\eta\eta_p} - I_{\xi\xi_p} + I_{\zeta\zeta_p}) \cos \beta - 2 I_{\xi\eta_p} \sin \beta]$$

$$+ 2 \omega_z (I_{\eta\zeta_p} - I_{\zeta\xi_p}) \qquad \text{(D-43)}$$

$$A_7 = I_{\eta\zeta_p} \sin \beta - I_{\zeta\xi_p} \cos \beta \qquad \text{(D-44)}$$

$$A_8 = -(I_{\zeta\xi_p} \sin \beta + I_{\eta\zeta_p} \cos \beta) \qquad \text{(D-45)}$$

$$A_9 = I_{\zeta\zeta_p} \dot{\omega}_z - [I_{\eta\eta_p} - I_{\xi\xi_p}][(\omega_x \cos \alpha' + \omega_y \sin \alpha')(\omega_x \sin \alpha' - \omega_y \cos \alpha')]$$

$$+ I_{\zeta\xi_p} [\omega_z (\omega_x \sin \alpha' - \omega_y \sin \alpha') + (\dot{\omega}_x \cos \alpha' + \dot{\omega}_y \sin \alpha')]$$

$$- I_{\eta\zeta_p} [(\dot{\omega}_x \sin \alpha' - \dot{\omega}_y \cos \alpha') - \omega_z (\omega_x \cos \alpha' + \omega_y \sin \alpha')]$$

$$- I_{\xi\eta_p} [(\omega_x \cos \alpha' + \omega_y \sin \alpha')^2 - (\omega_x \sin \alpha' - \omega_y \cos \alpha')^2] \qquad \text{(D-46)}$$

$$A_{10} = I_{\zeta\zeta_p} \qquad \text{(D-47)}$$

Simplification of Force and Moment Equations. In order to be able to solve for the upper and lower pivot forces, both the force and moment component equations are now rewritten in an appropriate simplified form.

x'-Component of the Force Equation

Equation D-27 becomes:

$$-F_{x'u} + A_{11} F_{y'u} + F_{x'L} - A_{11} F_{y'L}$$
$$= A_{12} + A_{13} \dot{\psi} + A_{14} \dot{\psi}^2 + A_{15} \ddot{\psi} + P_n A_{16} \qquad \text{(D-48)}$$

where

$$A_{11} = \mu_1 s_5 \qquad \text{(D-49)}$$

$$A_{12} = m_p r_{cp} [- \omega_x^2 \sin \beta_3 \sin \alpha' - \omega_y^2 \cos \beta_3 \cos \alpha'$$
$$+ \omega_x \omega_y \sin (\alpha' + \beta_3) - \omega_z^2 \cos \beta - \dot{\omega}_z \sin \beta] + m_p K_x \qquad \text{(D-50)}$$

$$A_{13} = - 2 \omega_z m_p r_{cp} \cos \beta \qquad \text{(D-51)}$$

$$A_{14} = - m_p r_{cp} \cos \beta \qquad \text{(D-52)}$$

$$A_{15} = - m_p r_{cp} \sin \beta \qquad \text{(D-53)}$$

$$A_{16} = - [\mu_1 s_4 \cos (\psi + \alpha) - \sin (\psi + \alpha)] \qquad \text{(D-54)}$$

y'-Component of the Force Equation

Equation D-28 becomes:

$$-A_{11} F_{x'u} - F_{y'u} + A_{11} F_{x'L} + F_{y'L}$$
$$= A_{17} + A_{18} \dot{\psi} + A_{19} \dot{\psi}^2 + A_{20} \ddot{\psi} + A_{21} P_n \qquad \text{(D-55)}$$

where

$$A_{17} = m_p r_{cp} [- \omega_x^2 \cos \beta_3 \sin \alpha' + \omega_y^2 \sin \beta_3 \cos \alpha'$$
$$- \omega_x \omega_y \cos (\alpha' + \beta_3) - \omega_z^2 \sin \beta + \dot{\omega}_z \cos \beta] + m_p K_y \qquad \text{(D-56)}$$

$$A_{18} = - 2 m_p r_{cp} \omega_z \sin \beta \qquad \text{(D-57)}$$

$$A_{19} = - m_p \; r_{cp} \sin \beta \tag{D-58}$$

$$A_{20} = m_p \; r_{cp} \cos \beta \tag{D-59}$$

$$A_{21} = - \left[\cos (\psi + \alpha) + \mu_1 s_4 \sin (\psi + \alpha)\right] \tag{D-60}$$

z'-Component of the Force Equation

Equation D-29 is rewritten to read:

$$\tilde{F}_{z'} = A_{22} + A_{23} \, \dot{\psi} \tag{D-61}$$

The tilde is now used to indicate the conservative nature of this force, when the terms A_{22} and A_{23} are made absolute.

Thus

$$A_{22} = \left| m_p \; r_{cp} \left[- (\dot{\omega}_x + \omega_y \omega_z) \sin \alpha' + (\dot{\omega}_y - \omega_x \omega_z) \cos \alpha' \right] + m_p \; K_z \right| \tag{D-62}$$

and

$$A_{23} = \left| - 2 \; m_p \; r_{cp} \; (\omega_x \cos \alpha' + \omega_y \sin \alpha') \right| \tag{D-63}$$

The absolute values in the above expressions will be useful later (eq D-123).

x' - Component of Moment Equation

The x'-component of equation D-30 is obtained with the help of the x'-components of equations D-32 and D-33, as well as equation D-35. Therefore,

$$\begin{aligned} & L_u \; A_{11} \; F_{x'u} + L_u \; F_{y'u} + L_L \; A_{11} \; F_{x'L} + L_L \; F_{y'L} \\ & \quad = m_p \; r_{cp} \; K_z \sin \beta + A_1 + \dot{\psi} A_2 + \dot{\psi}^2 A_3 + \ddot{\psi} A_4 \end{aligned} \tag{D-64}$$

y'-Component of the Moment Equation

The y'-component of equation D-30 is obtained with the help of the y'-components of equations D-32 and D-33, as well as equation D-36:

$$\begin{aligned} & - L_u \; F_{x'u} + L_u \; A_{11} \; F_{y'u} - L_L \; F_{x'L} + L_L \; A_{11} \; F_{y'L} \\ & \quad = - m_p \; r_{cp} \; K_z \cos \beta + A_5 + A_6 \; \dot{\psi} + A_7 \; \dot{\psi}^2 + A_8 \; \ddot{\psi} \end{aligned} \tag{D-65}$$

z'-Components of the Moment Equation

The z'-component of equation D-30 is composed of the z'-components of equations D-32 and D-33, as well as equation D-37:

$$P_n \left(D_1' - \mu_1 s_4 C_1'\right) - \rho_f A_{11} F_{z'} - \rho_p A_{11} F_{y'u} - \rho_p A_{11} F_{x'u}$$

$$- \rho_p A_{11} F_{y'L} - \rho_p A_{11} F_{x'L}$$

$$= - m_p r_{cp} \left(K_x \sin \beta - K_y \cos \beta\right) + A_9 + A_{10} \ddot{\psi} \qquad \text{(D-66)}$$

Solution for Pallet Pivot Forces. The force $F_{x'u}$, $F_{y'u}$, $F_{x'L}$, and $F_{y'L}$ are obtained from the simultaneous solution of equations D-48, D-55, D-64, and D-65. The force $F_{z'}$ is given by equation D-61. These five forces are eventually substituted into equation D-66, and the resulting expression is solved for the contact force P_n.

The simultaneous set of equations becomes

$$\begin{bmatrix} -1 & A_{11} & 1 & -A_{11} \\ -A_{11} & -1 & A_{11} & 1 \\ L_u A_{11} & L_u & L_L A_{11} & L_L \\ -L_u & L_u A_{11} & -L_L & L_L A_{11} \end{bmatrix} \begin{bmatrix} F_{x'u} \\ F_{y'u} \\ F_{x'L} \\ F_{y'L} \end{bmatrix} = \begin{bmatrix} B_{p1} \\ B_{p2} \\ B_{p3} \\ B_{p4} \end{bmatrix} \qquad \text{(D-67)}$$

where

$$B_{p1} = A_{12} + A_{13} \dot{\psi} + A_{14} \dot{\psi}^2 + A_{15} \ddot{\psi} + P_n A_{16} \qquad \text{(D-68)}$$

$$B_{p2} = A_{17} + A_{18} \dot{\psi} + A_{19} \dot{\psi}^2 + A_{20} \ddot{\psi} + P_n A_{21} \qquad \text{(D-69)}$$

$$B_{p3} = m_p r_{cp} K_z \sin \beta + A_1 + A_2 \dot{\psi} + A_3 \dot{\psi}^2 + A_4 \ddot{\psi} \qquad \text{(D-70)}$$

$$B_{p4} = - m_p r_{cp} K_z \cos \beta + A_5 + A_6 \dot{\psi} + A_7 \dot{\psi}^2 + A_8 \ddot{\psi} \qquad \text{(D-71)}$$

Cramer's rule will now be used to determine the four pivot forces $F_{x'u}$, $F_{y'u}$, $F_{x'L}$, and $F_{y'L}$. To this end, the coefficient determinant D must be found first.

Evaluation of the Coefficient Determinant D

The coefficient determinant of equation D-67 is given by:

$$D = \begin{vmatrix} -1 & A_{11} & 1 & -A_{11} \\ -A_{11} & -1 & A_{11} & 1 \\ L_u A_{11} & L_u & L_L A_{11} & L_L \\ -L_u & L_u A_{11} & -L_L & L_L A_{11} \end{vmatrix} \quad \text{(D-72)}$$

Evaluation of the above furnishes:

$$D = [(L_u + L_L)\,(1 + A_{11}{}^2)]^2 \quad \text{(D-73)}$$

Since, according to equation D-49

$$A_{11} = \mu_1\, s_5 \quad \text{(D-74)}$$

and s_5^2 is always equal to unity (eq D-22), the coefficient determinant becomes

$$D = [(L_u + L_L)\,(1 + \mu_1^2)]^2 \quad \text{(D-75)}$$

Evaluation of Pivot Force $\tilde{F}_{x'u}$

The pivot force $F_{x'u}$ is obtained from

$$F_{x'u} = \frac{D_{F_{x'u}}}{D} \quad \text{(D-76)}$$

where

$$D_{F_{x'u}} = \begin{vmatrix} B_{p1} & A_{11} & 1 & -A_{11} \\ B_{p2} & -1 & A_{11} & 1 \\ B_{p3} & L_u & L_L A_{11} & L_L \\ B_{p4} & L_u A_{11} & -L_L & L_L A_{11} \end{vmatrix} \quad \text{(D-77)}$$

Evaluation of $D_{F_{x'u}}$ furnishes:

$$D_{F_{x'u}} = (L_u + L_L)(1 + A_{11}^{\ 2})[- L_L B_{p1} - A_{11} L_L B_{p2} + A_{11} B_{p3} - B_{p4}] \quad \text{(D-78)}$$

After substitution of

$$A_{11}^{\ 2} = \mu_1^2 \quad \text{(D-79)}$$

the following is obtained

$$D_{F_{x'u}} = (L_u + L_L)(1 + \mu_1^2)[- L_L B_{p1} - A_{11} L_L B_{p2} + A_{11} B_{p3} - B_{p4}] \quad \text{(D-80)}$$

Subsequently, equations D-49 and D-68 to D-71 are substituted into the above and the coefficients of similar terms are collected and made absolute. The latter is done to get conservative pivot and friction forces. This leads to:

$$D_{F_{x'u}} = (L_u + L_L)(1 + \mu_1^2)\,[C_1 + C_2 \dot{\psi} + C_3 \dot{\psi}^2 + C_4 \ddot{\psi} + C_5 P_n] \quad \text{(D-81)}$$

where

$$C_1 = |- L_L A_{12} + \mu_1 s_5 (A_1 - L_L A_{17}) - A_5 + m_p r_{cp} K_z (\mu_1 s_5 \sin\beta + \cos\beta)| \quad \text{(D-82)}$$

$$C_2 = |- L_L A_{13} + \mu_1 s_5 (A_2 - L_L A_{12}) - A_6| \quad \text{(D-83)}$$

$$C_3 = |- L_L A_{14} + \mu_1 s_5 (A_3 - L_L A_{19}) - A_7| \quad \text{(D-84)}$$

$$C_4 = |- L_L A_{15} + \mu_1 s_5 (A_4 - L_L A_{20}) - A_8| \quad \text{(D-85)}$$

$$C_5 = |- L_L A_{16} - \mu_1 s_5 L_L A_{21}| \quad \text{(D-86)}$$

Finally, substitution of equations D-75 and D-81 into equation D-76 gives the now tilded pivot force

$$\tilde{F}_{x'u} = \frac{1}{(L_u + L_L)(1 + \mu_1^2)}[C_1 + C_2 \dot{\psi} + C_3 \dot{\psi}^2 + C_4 \ddot{\psi} + C_5 P_n] \quad \text{(D-87)}$$

Evaluation of Pivot force $\tilde{F}_{y'u}$

The pivot force $F_{y'u}$ is again obtained with Cramer's rule, i.e.,

$$F_{y'u} = \frac{D_{F_{y'u}}}{D} \quad \text{(D-88a)}$$

where

$$D_{F_{y'u}} = \begin{vmatrix} -1 & B_{p1} & 1 & -A_{11} \\ -A_{11} & B_{p2} & A_{11} & 1 \\ L_u A_{11} & B_{p3} & L_L A_{11} & L_L \\ -L_u & B_{p4} & -L_L & L_L A_{11} \end{vmatrix} \quad \text{(D-88b)}$$

Evaluation of $D_{F_{y'u}}$ furnishes:

$$D_{F_{y'u}} = (L_u + L_L)(1 + A_{11}^{\,2})\,(A_{11}\,L_L\,B_{p1} - L_L\,B_{p2} + B_{p3} + A_{11}\,B_{p4}) \quad \text{(D-89)}$$

and again, with $A_{11} = s_5\mu_1$

$$D_{F_{y'u}} = (L_u + L_L)(1 + \mu_1^2)\,(\mu_1 s_5\,L_L\,B_{p1} - L_L\,B_{p2} + B_{p3} + \mu_1 s_5\,B_{p4}) \quad \text{(D-90)}$$

Appropriate substitution into equation D-88a and proceeding in a manner parallel to that followed in the determination of $\tilde{F}_{x'u}$, the following is obtained for $\tilde{F}_{y'u}$

$$\tilde{F}_{y'u} = \frac{1}{(L_u + L_L)(1 + \mu_1^2)}\,[C_6 + C_7\,\dot{\psi} + C_8\,\dot{\psi}^2 + C_9\,\ddot{\psi} + C_{10}\,P_n] \quad \text{(D-91)}$$

where

$$C_6 = |A_1 - L_L\,A_{17} + \mu_1 s_5\,(L_L\,A_{12} + A_5) + m_p\,r_{cp}\,K_z\,(\sin\beta - \mu_1 s_5\,\cos\beta)| \quad \text{(D-92)}$$

$$C_7 = |A_2 - L_L\,A_{18} + \mu_1 s_5\,(A_6 + L_L\,A_{13})| \quad \text{(D-93)}$$

$$C_8 = |A_3 - L_L\,A_{19} + \mu_1 s_5\,(A_7 + L_L\,A_{14})| \quad \text{(D-94)}$$

$$C_9 = |A_4 - L_L A_{20} + \mu_1 s_5 (L_L A_{15} - A_8)| \tag{D-95}$$

$$C_{10} = |\mu_1 s_5 L_L A_{16} - L_L A_{21}| \tag{D-96}$$

Evaluation of Pivot Force $\tilde{F}_{x'L}$

The pivot force $F_{x'L}$ is obtained from

$$F_{x'L} = \frac{D_{F_{x'L}}}{D} \tag{D-97}$$

where

$$D_{F_{x'L}} = \begin{vmatrix} -1 & A_{11} & B_{p1} & -A_{11} \\ -A_{11} & -1 & B_{p2} & 1 \\ L_u A_{11} & L_u & B_{p3} & L_L \\ -L_u & L_u A_{11} & B_{p4} & L_L A_{11} \end{vmatrix} \tag{D-98}$$

Evaluation of $D_{F_{x'L}}$ furnishes:

$$D_{F_{x'L}} = (L_u + L_L)(1 + A_{11}{}^2)\ (L_u\ B_{p1} + L_u\ A_{11}\ B_{p2} + A_{11}\ B_{p3} - B_{p4}) \tag{D-99}$$

and again, with $A_{11} = s_5 \mu_1$

$$D_{F_{x'L}} = (L_u + L_L)(1 + \mu_1^2)\ (L_u\ B_{p1} + \mu_1 s_5\ L_u\ B_{p2} + \mu_1 s_5\ B_{p3} - B_{p4}) \tag{D-100}$$

Proceeding as before to obtain $\tilde{F}_{x'L}$, the following is found:

$$\tilde{F}_{x'L} = \frac{1}{(L_u + L_L)(1 + \mu_1^2)} [C_{11} + C_{12}\ \dot{\psi} + C_{13}\ \dot{\psi}^2 + C_{14}\ \ddot{\psi} + C_{15}\ P_n] \tag{D-101}$$

where

$$C_{11} = |L_u\ A_{12} - A_5 + \mu_1 s_5 (L_u\ A_{17} + A_1) + m_p\ r_{cp}\ K_z(\mu_1 s_5 \sin\beta + \cos\beta)| \tag{D-102}$$

$$C_{12} = |L_u\ A_{13} - A_6 + \mu_1 s_5\ (L_u\ A_{18} + A_2)| \tag{D-103}$$

$$C_{13} = |L_u A_{14} - A_7 + \mu_1 s_5 (L_u A_{19} + A_3)| \quad \text{(D-104)}$$

$$C_{14} = |L_u A_{15} - A_8 + \mu_1 s_5 (L_u A_{20} + A_4)| \quad \text{(D-105)}$$

$$C_{15} = |L_u A_{16} + \mu_1 s_5 L_u A_{21}| \quad \text{(D-106)}$$

Evaluation of Pivot Force $\tilde{F}_{y'L}$

The pivot force $F_{y'L}$ is obtained from:

$$F_{y'L} = \frac{D_{F_{y'L}}}{D} \quad \text{(D-107)}$$

where

$$D_{F_{y'L}} = \begin{vmatrix} -1 & A_{11} & 1 & B_{p1} \\ -A_{11} & -1 & A_{11} & B_{p2} \\ L_u A_{11} & L_u & L_L A_{11} & B_{p3} \\ -L_u & L_u A_{11} & -L_L & B_{p4} \end{vmatrix} \quad \text{(D-108)}$$

Evaluation of $D_{F_{y'L}}$ furnishes:

$$D_{F_{y'L}} = (L_u + L_L)(1 + A_{11}{}^2)[- L_u A_{11} B_{p1} + L_u B_{p2} + B_{p3} + A_{11} B_{p4}] \quad \text{(D-109)}$$

and again, with $A_{11} = s_5 \mu_1$

$$D_{F_{y'L}} = (L_u + L_L)(1 + \mu_1^2) [- \mu_1 s_5 L_u B_{p1} + L_u B_{p2} + B_{p3} + \mu_1 s_5 B_{p4}] \quad \text{(D-110)}$$

$\tilde{F}_{y'L}$ is found from equation D-107 in a manner shown earlier:

$$\tilde{F}_{y'L} = \frac{1}{(L_u + L_L)(1 + \mu_1^2)} [C_{16} + C_{17} \dot{\psi} + C_{18} \dot{\psi}^2 + C_{19} \ddot{\psi} + C_{20} P_n] \quad \text{(D-111)}$$

where

$$C_{16} = |L_u A_{17} + A_1 + \mu_1 s_5 (A_5 - L_u A_{12}) + m_p r_{cp} K_z (\sin \beta - \mu_1 s_5 \cos \beta)| \quad \text{(D-112)}$$

$$C_{17} = \left| L_u A_{18} + A_2 + \mu_1 s_5 \left(A_6 - L_u A_{13}\right)\right| \tag{D-113}$$

$$C_{18} = \left| L_u A_{19} + A_3 + \mu_1 s_5 \left(A_7 - L_u A_{14}\right)\right| \tag{D-114}$$

$$C_{19} = \left| L_u A_{20} + A_4 + \mu_1 s_5 \left(A_8 - L_u A_{15}\right)\right| \tag{D-115}$$

$$C_{20} = \left| L_u A_{21} - \mu_1 s_5 L_u A_{16}\right| \tag{D-116}$$

Substitution of Conservative (Tilded) Pivot Forces Into the z'-Moment Equation. Rather than substitute the forces $F_{x'u}$, $F_{y'u}$, $F_{x'L}$, $F_{y'L}$, and $F_{z'L}$ into the z'-moment equation D-66, the associated tilded, conservative expressions, as given by equations D-61, D-87, D-91, D-101, and D-111 are used. To simplify matters, let the sum of $\tilde{F}_{x'u}$, $\tilde{F}_{y'u}$, $\tilde{F}_{x'L}$, and $\tilde{F}_{y'L}$ be first determined:

$$\tilde{F}_{x'u} + \tilde{F}_{y'u} + \tilde{F}_{x'L} + \tilde{F}_{y'L}$$

$$= A_{24} + A_{25}\, \dot{\psi} + A_{26}\, \dot{\psi}^2 + A_{27}\, \ddot{\psi} + A_{28}\, P_n \tag{D-117}$$

where

$$A_{24} = \frac{C_1 + C_6 + C_{11} + C_{16}}{L_T\left(1 + \mu_1^2\right)} \tag{D-118}$$

$$A_{25} = \frac{C_2 + C_7 + C_{12} + C_{17}}{L_T\left(1 + \mu_1^2\right)} \tag{D-119}$$

$$A_{26} = \frac{C_3 + C_8 + C_{13} + C_{18}}{L_T\left(1 + \mu_1^2\right)} \tag{D-120}$$

$$A_{27} = \frac{C_4 + C_9 + C_{14} + C_{19}}{L_T\left(1 + \mu_1^2\right)} \tag{D-121}$$

$$A_{28} = \frac{C_5 + C_{10} + C_{15} + C_{20}}{L_T\left(1 + \mu_1^2\right)} \tag{D-122a}$$

and

$$L_T = L_u + L_L \tag{D-122b}$$

Substitution of the above, as well as equation D-61 into equation D-66, and letting $A_{11} = \mu_1 s_5$ according to equation D-49 leads to the following provisional z'-moment expression:

$$P_n \left(D_1' - \mu_1 s_4 C_1'\right) - \rho_f \, \mu_1 s_5 \left(A_{22} \pm A_{23} \, \dot{\psi}\right)$$

$$- \rho_p \, \mu_1 s_5 \left[A_{24} \pm \dot{\psi} \, A_{25} \pm \dot{\psi}^2 \, A_{26} \pm \ddot{\psi} \, A_{27} + P_n \, A_{28}\right]$$

$$= - m_p \, r_{cp} \left(K_x \sin \beta - K_y \cos \beta\right) + A_9 + A_{10} \, \ddot{\psi} \tag{D-123}$$

To make sure that all friction moments act in a direction opposite to the instantaneous rotation of the pallet, the signs of those friction terms which depend on ψ, $\dot{\psi}$, or ψ have been left undecided for the moment. They will be resolved below.

Before these decisions are made, let equation D-123 be rewritten as follows:

$$P_n \left[D_1' - C_1' \, \mu_1 s_4 - \rho_p \, \mu_1 s_5 \, A_{28}\right] - \mu_1 s_5 \left[\rho_f \, A_{22} + \rho_p \, A_{24}\right]$$

$$\pm \mu_1 s_5 \left[\rho_f \, A_{23} + \rho_p \, A_{25}\right] \dot{\psi} \pm \rho_p \, \mu_1 s_5 \, A_{26} \, \dot{\psi}^2 \pm \rho_p \, \mu_1 s_5 \, A_{27} \, \ddot{\psi}$$

$$= A_{10} \, \ddot{\psi} + A_9 - m_p \, r_{cp} \left(K_x \sin \beta - K_y \cos \beta\right) \tag{D-124}$$

With s_5 positive for positive rotation of the verge and vice versa and with all other parameters positive at all times, the following moment components of equation D-124 must have negative signs during positive rotation:

$$- P_n \, \rho_p \, \mu_1 s_5 \, A_{28} \tag{D-125}$$

$$- \mu_1 s_5 \left[\rho_f \, A_{22} + \rho_p \, A_{24}\right] \tag{D-126}$$

$$- \rho_p \, \mu_1 s_5 \, A_{26} \, \dot{\psi}^2 \tag{D-127}$$

The sign of the term containing $\dot{\psi}$ must be negative for a positive $\dot{\psi}$ and vice versa. Therefore, the sign of $\dot{\psi}$ can be used to control the sign of this term, and the signum operator s_5 may be omitted. This term becomes:

$$- \mu_1 \left[\rho_f \, A_{23} + \rho_p \, A_{25}\right] \dot{\psi} \tag{D-128}$$

The choice of sign for the term containing the pallet angular acceleration is discussed in detail in appendix F of reference 2. This work leads to the computational rules of equations D-134 and D-135 below. These rules deal with the sign in the effective moment of inertia I_{PR}. (Note that the signum function s_5 has been omitted in these expressions.)

With the above considerations, equation D-124 becomes:

$$P_n A_{29} - A_{30} - A_{31} \dot{\psi} - A_{32} \dot{\psi}^2$$

$$= I_{PR} \ddot{\psi} + A_9 - m_p r_{cp} (K_x \sin \beta - K_y \cos \beta) \quad \text{(D-129)}$$

where

$$A_{29} = D_1' - C_1' \mu_1 s_4 - \rho_p \mu_1 s_5 A_{28} \quad \text{(D-130)}$$

$$A_{30} = \mu_1 s_5 (\rho_f A_{22} + \rho_p A_{24}) \quad \text{(D-131)}$$

$$A_{31} = \mu_1 (\rho_f A_{23} + \rho_p A_{25}) \quad \text{(D-132)}$$

$$A_{32} = \mu_1 s_5 \rho_p A_{26} \quad \text{(D-133)}$$

$$I_{PR} = I_{\zeta\zeta_p} + A_{333}, \text{ when } \dot{\psi} \text{ and } \ddot{\psi} \text{ have identical signs} \quad \text{(D-134)}$$

$$I_{PR} = I_{\zeta\zeta_p} - A_{333}, \text{ when } \dot{\psi} \text{ and } \ddot{\psi} \text{ have opposite signs*} \quad \text{(D-135)}$$

$$A_{333} = \mu_1 \rho_p A_{27} \quad \text{(D-136)}$$

Equation D-129 is now rewritten to find an expression for the contact force P_n:

$$P_n = \frac{I_{PR} \ddot{\psi} + A_9 + A_{30} + A_{31} \dot{\psi} + A_{32} \dot{\psi}^2 - m_p r_{cp} (K_x \sin \beta - K_y \cos \beta)}{A_{29}} \quad \text{(D-137)}$$

The above expression is now changed to reflect the escape wheel angular velocity and angular acceleration $\dot{\phi}$ and $\ddot{\phi}$, respectively, so that it may later be equated to an expression for the escape wheel. Equations B-19 and B-26 of appendix B of reference 1 show the following relationships:

$$\dot{\psi} = \dot{\phi} U \quad \text{(D-138)}$$

---

* $I_p - A_{333}$ must not become negative. If this occurs I_{PR} must be set equal to zero.

and

$$\ddot{\psi} = U \ddot{\phi} + V \dot{\phi}^2 \tag{D-139}$$

U and V may be obtained from reference 1. This leads to:

$$P_n = \frac{1}{A_{29}} \left[I_{PR} U \ddot{\phi} + \left(A_{32} U^2 + I_{PR} V\right) \dot{\phi}^2 \right.$$

$$\left. + A_{31} U \dot{\phi} + A_9 + A_{30} - m_p r_{cp} \left(K_x \sin \beta - K_y \cos \beta\right) \right] \tag{D-140}$$

Force Equations for Escape Wheel and Pinion No. 3. How the contact forces $\bar{P}_n$ and $\bar{F}_{23}$, together with their associated friction forces, act on the escape wheel and pinion no. 3 combination is shown in figure D-4a. A separate free body diagram of the pivot shaft of the escape wheel is shown in figure D-4b. All these forces are now defined in the projectile (fuze) fixed X-Y-Z system. This makes it necessary to transform the unit vectors $\bar{n}_t$ and $\bar{n}_n$ from the x'-y' to the X-Y system (eqs D-25 and D-26 as well as eqs B-79 to B-82 of reference 1).

Since

$$\bar{i}' = - \cos \beta_3 \bar{I} - \sin \beta_3 \bar{J} \tag{D-141}$$

and

$$\bar{j}' = \sin \beta_3 \bar{I} - \cos \beta_3 \bar{J} \tag{D-142}$$

the previous unit vectors become:

$$\bar{n}_t = - \cos \left(\psi + \alpha + \beta_3\right) \bar{I} - \sin \left(\psi + \alpha + \beta_3\right) \bar{J} \tag{D-143}$$

$$\bar{n}_n = \sin \left(\psi + \alpha + \beta_3\right) \bar{I} - \cos \left(\psi + \alpha + \beta_3\right) \bar{J} \tag{D-144}$$

The force equations for the escape wheel in coupled motion are generally obtained from Newton's law:

$$\Sigma \bar{F} = m_3 \bar{A}_{O_s/\text{ground}} \tag{D-145}$$

where

$\Sigma \bar{F}$ = sum of pivot forces as well as contact forces P_n and F_{23} and their associated friction forces

m_3 = mass of escape wheel and pinion no. 3

Escape wheel rotates CCW

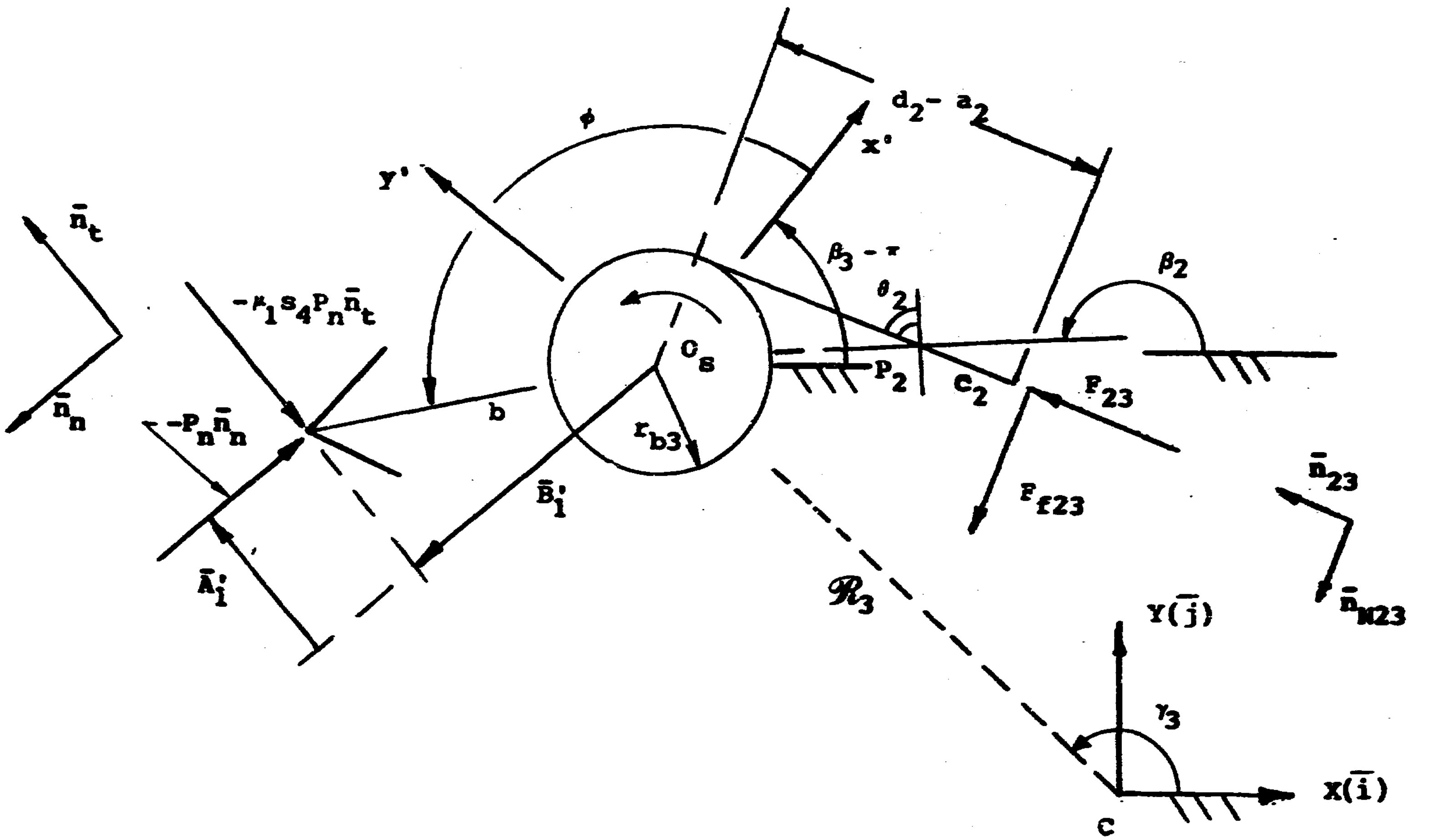


Figure D-4a. Top view free body diagram of escape wheel and pinion no. 3 in entrance coupled motion

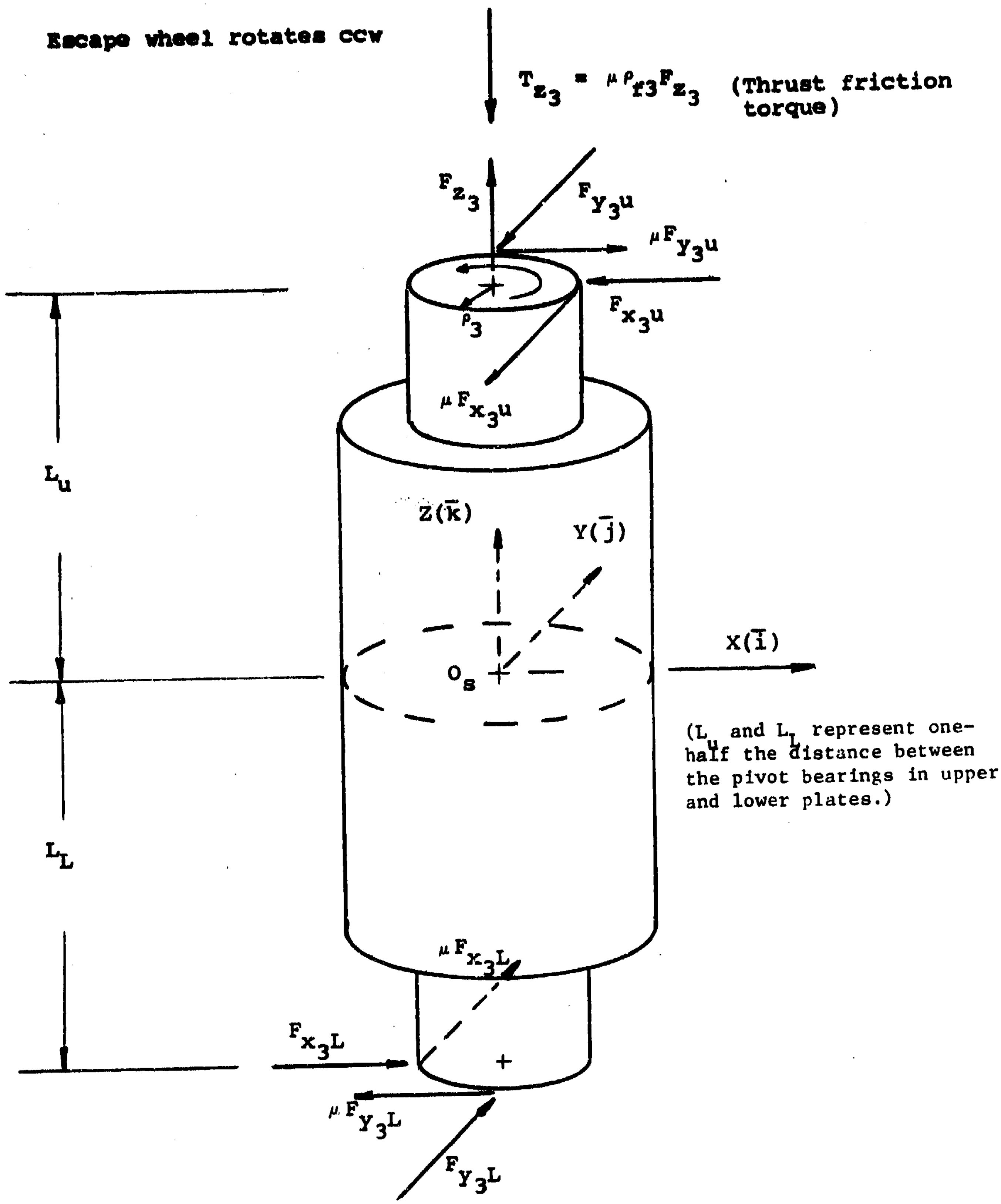


Figure D-4b. Escape wheel and pinion no. 3 in entrance coupled motion. Normal forces, friction forces, and thrust friction torque acting on escape wheel pivots.

$\bar{A}_{0_s/\text{ground}}$ = acceleration of escape wheel center of mass, which lies on axis of rotation, with respect to ground. Therefore

$$\bar{A}_{0_s/\text{ground}} = \bar{A}_{0_s/C} + \bar{A}_{C/\text{ground}} \qquad \text{(D-146)}$$

In the above, $\bar{A}_{C/\text{ground}}$, the acceleration of the fuze geometric center C with respect to the ground is given in terms of the X-Y-Z system by equation C-4 of appendix C. The acceleration of the escape wheel center of mass with respect to the above point C, i.e., $A_{0_s/C}$, becomes:

$$\bar{A}_{0_s/C} = \bar{\omega}_x \times (\bar{\omega}_x \times \mathcal{R}_3\ \bar{n}_3) + \dot{\bar{\omega}} \times \mathcal{R}_3 \bar{n}_3 \qquad \text{(D-147)}$$

where

$$\bar{n}_3 = \cos\gamma_3\ \bar{i} + \sin\gamma_3\ \bar{j} \qquad \text{(D-148)}$$

Substitution of

$$\bar{\omega} = \omega_x\ \bar{i} + \omega_y\ \bar{j} + \omega_z\ \bar{k} \qquad \text{(D-149)}$$

according to equation A-1 and

$$\dot{\bar{\omega}} = \dot{\omega}_x\ \bar{i} + \dot{\omega}_y\ \bar{j} + \dot{\omega}_z\ \bar{k} \qquad \text{(D-150)}$$

according to equation A-5, with

$$_{3x} = \mathcal{R}_3 \cos\gamma_3 \qquad \text{(D-151)}$$

and

$$_{3y} = \mathcal{R}_3 \sin\gamma_3 \qquad \text{(D-152)}$$

results in:

$$\bar{A}_{0_s/C} = J_x\ \bar{i} + J_y\ \bar{j} + J_z\ \bar{k} \qquad \text{(D-153)}$$

where

$$J_x = \omega_x\ \omega_y\ \mathcal{R}_{3y} - (\omega_y^{\ 2} + \omega_z^{\ 2})\ \mathcal{R}_{3x} - \dot{\omega}_z\ \mathcal{R}_{3y} \qquad \text{(D-154)}$$

$$J_y = \omega_x\ \omega_y\ \mathcal{R}_{3x} - (\omega_x^{\ 2} + \omega_z^{\ 2})\ \mathcal{R}_{3y} + \dot{\omega}_z\ \mathcal{R}_{3x} \qquad \text{(D-155)}$$

$$J_z = (\omega_x \mathcal{R}_{3x} + \omega_y \mathcal{R}_{3y})\ \omega_z + \dot{\omega}_x \mathcal{R}_{3y} - \dot{\omega}_y \mathcal{R}_{3x} \qquad \text{(D-156)}$$

Equation D-153 is now substituted together with equation C-3 into equation D-146:

$$\bar{A}_{0_s/\text{ground}} = N_x \bar{i} + N_y \bar{j} + N_z \bar{k} \tag{D-157}$$

where

$$N_x = G_x + J_x \tag{D-158}$$

$$N_y = G_y + J_y \tag{D-159}$$

$$N_z = G_z + J_z \tag{D-160}$$

The vectorial force equation is now obtained with the help of figures D-4a and D-5b, and equation D-145:

$$\begin{aligned} &-P_n \bar{n}_n - \mu_1 s_4 P_n \bar{n}_t + F_{23} \bar{n}_{23} + \mu s_2 F_{23} \bar{n}_{N23} \\ &+ F_{z3} \bar{k} - F_{x3u} \bar{i} - F_{y3u} \bar{j} - \mu F_{x3u} \bar{j} + \mu F_{y3u} \bar{i} \\ &+ F_{x3L} \bar{i} + F_{y3L} \bar{j} + \mu F_{x3L} \bar{j} - \mu F_{y3L} \bar{i} \\ &\quad = \left(N_x \bar{i} + N_y \bar{j} + N_z \bar{k}\right) m_3 \end{aligned} \tag{D-161}$$

$\bar{n}_t$ and $\bar{n}_n$ are now substituted according to equations D-143 and D-144. The unit vectors $\bar{n}_{23}$ and $\bar{n}_{N23}$ are taken from reference 1, i.e.,

$$\bar{n}_{23} = \sin\left(\beta_2 + \theta_2\right) \bar{i} - \cos\left(\beta_2 + \theta_2\right) \bar{j} \tag{D-162}$$

$$\bar{n}_{N23} = \cos\left(\beta_2 + \theta_2\right) \bar{i} + \sin\left(\beta_2 + \theta_2\right) \bar{j} \tag{D-163}$$

This leads to the following force component equations:

$$\begin{aligned} &-P_n \sin\left(\psi + \alpha + \beta_3\right) + \mu_1 s_4 P_n \cos\left(\psi + \alpha + \beta_3\right) \\ &+ F_{23} \sin\left(\beta_2 + \theta_2\right) + \mu s_2 F_{23} \cos\left(\beta_2 + \theta_2\right) - F_{x3u} \\ &+ \mu F_{y3u} + F_{x3L} - \mu F_{y3L} = N_x m_3 \end{aligned} \tag{D-164}$$

$$P_n \cos(\psi + \alpha + \beta_3) + \mu_1 s_4 P_n \sin(\psi + \alpha + \beta_3)$$

$$- F_{23} \cos(\beta_2 + \theta_2) + \mu s_2 F_{23} \sin(\beta_2 + \theta_2) - F_{y3u}$$

$$- \mu F_{x3u} + F_{y3L} + \mu F_{x3L} = N_y m_3 \qquad \text{(D-165)}$$

$$F_{z3} = N_z m_3 \qquad \text{(D-166)}$$

Moment Equations for the Escape Wheel and Pinion No. 3. Since the escape wheel and pinion no. 3 represents a symmetrical body, its moment equation may be expressed in terms of the projectile-fixed X-Y-Z system according to equation B-13 of appendix B. Adaptation of this expression to the escape wheel system furnishes:

$$\bar{M}_{O_s} = [I_{xs} \dot{\omega}_x + I_{zs} \omega_y (\omega_z + \dot{\phi}) - I_{ys} \omega_y \omega_z] \bar{i}$$

$$+ [I_{ys} \dot{\omega}_y + I_{xs} \omega_x \omega_z - I_{zs} \omega_x (\omega_z + \dot{\phi})] \bar{j}$$

$$+ I_{zs} (\dot{\omega}_z + \ddot{\phi}) \bar{k} \qquad \text{(D-167)}$$

The moment sum $\bar{M}_{O_s}$ about point O_s is now found with the help of the free body diagrams of figures D-4a and D-4b. Reference 1 is also useful.

$$\bar{M}_{O_s} = -P_n(A_1' - B_1' \mu_1 s_4)\bar{k} + r_{b3} F_{23} \bar{k} - \mu s_2 (d_2 - a_2) F_{23} \bar{k} - \mu \rho_{f3} F_{z3} \bar{k}$$

$$+ (L_u \bar{k} + \rho_3 \bar{j}) \times (-F_{y3u} \bar{j} + \mu F_{y3u} \bar{i})$$

$$+ (L_u \bar{k} + \rho_3 \bar{i}) \times (- F_{x3u} \bar{i} - \mu F_{x3u} \bar{j})$$

$$+ (-L_L \bar{k} - \rho_3 \bar{j}) \times (F_{y3L} \bar{j} - \mu F_{y3L} \bar{i})$$

$$+ (-L_L \bar{k} - \rho_3 \bar{i}) \times (F_{x3L} \bar{i} + \mu F_{x3L} \bar{j}) \qquad \text{(D-168)}$$

The term $-\mu \rho_{f3} F_{z3}$ represents the thrust friction moment due to force F_{z3} (eq D-166). The term ρ_{f3} stands for the thrust friction radius of the escape wheel pivot. Equation D-168 becomes:

$$\bar{M}_{O_s} = \left[L_u F_{y3u} + L_u \mu F_{x3u} + L_L F_{y3L} + L_L \mu F_{x3L}\right] \bar{i}$$

$$+ \left[L_u \mu F_{y3u} - L_u F_{x3u} + L_L \mu F_{y3L} - L_L F_{x3L}\right] \bar{j}$$

$$+ \left[- P_n \left(A_1' - B_1' \mu_1 s_4\right) + r_{b3} F_{23} - \mu s_2 \left(d_2 - a_2\right) F_{23}\right.$$

$$- \mu \rho_{f3} F_{z3} - \rho_3 \mu F_{y3u} - \rho_3 \mu F_{x3u}$$

$$\left. - \rho_3 \mu F_{y3L} - \rho_3 \mu F_{x3L}\right] \bar{k} \qquad \text{(D-169)}$$

Substitution of equation D-169 into equation D-167 leads to the following moment component expressions:

$$L_u \mu F_{x3u} + L_u F_{y3u} + L_L \mu F_{x3L} + L_L F_{y3L}$$

$$= I_{xs} \dot{\omega}_x + I_{zs} \omega_y \left(\omega_z + \dot{\phi}\right) - I_{ys} \omega_y \omega_z \qquad \text{(D-170)}$$

$$-L_u F_{x3u} + L_u \mu F_{y3u} - L_L F_{x3L} + L_L \mu F_{y3L}$$

$$= I_{ys} \dot{\omega}_y + I_{xs} \omega_x \omega_z - I_{zs} \omega_x \left(\omega_z + \dot{\phi}\right) \qquad \text{(D-171)}$$

$$- P_n \left(A_1' - B_1' \mu_1 s_4\right) + F_{23} \left[r_{b3} - \mu s_2 \left(d_2 - a_2\right)\right]$$

$$- \mu \rho_{f3} F_{z3} - \mu \rho_3 \left[F_{x3u} + F_{y3u} + F_{x3L} + F_{y3L}\right]$$

$$= I_{zs} \left(\dot{\omega}_z + \ddot{\phi}\right) \qquad \text{(D-172)}$$

Simplification of Force and Moment Equations. To solve for the pivot forces F_{x3u}, F_{y3u}, F_{x3L}, and F_{y3L}, the X and Y components of the force and moment equations must be rewritten in an appropriate form.

X-Component of Force Equation

Equation D-164 becomes

$$F_{x3u} - \mu F_{y3u} - F_{x3L} + \mu F_{y3L}$$

$$= P_n A_{33} + F_{23} A_{34} + A_{35} \qquad \text{(D-173)}$$

where

$$A_{33} = \mu_1 s_4 \cos(\psi + \alpha + \beta_3) - \sin(\psi + \alpha + \beta_3) \qquad \text{(D-174)}$$

$$A_{34} = \sin(\beta_2 + \theta_2) + \mu s_2 \cos(\beta_2 + \theta_2) \qquad \text{(D-175)}$$

$$A_{35} = - N_x m_3 \qquad \text{(D-176)}$$

Y-Component of Force Equation

Equation D-165 becomes:

$$\mu F_{x3u} + F_{y3u} - \mu F_{x3L} - F_{y3L} = P_n A_{36} + F_{23} A_{37} + A_{38} \qquad \text{(D-177)}$$

where

$$A_{36} = \cos(\psi + \alpha + \beta_3) + \mu_1 s_4 \sin(\psi + \alpha + \beta_3) \qquad \text{(D-178)}$$

$$A_{37} = \mu s_2 \sin(\beta_2 + \theta_2) - \cos(\beta_2 + \theta_2) \qquad \text{(D-179)}$$

$$A_{38} = - N_y m_3 \qquad \text{(D-180)}$$

Z-Component of Force Equation

Equation D-166 cannot be further simplified.

X-Component of Moment Equation

Equation D-170 becomes

$$\mu L_u F_{x3u} + L_u F_{y3u} + \mu L_L F_{x3L} + L_L F_{y3L}$$

$$= A_{39} + A_{40} \dot{\phi} \qquad \text{(D-181)}$$

where

$$A_{39} = I_{xs} \dot{\omega}_x + \omega_y \omega_z (I_{zs} - I_{ys}) \qquad \text{(D-182)}$$

$$A_{40} = I_{zs}\,\omega_y \tag{D-183}$$

Y-Component of Moment Equation

Equation D-171 becomes:

$$- L_u F_{x3u} + L_u \mu F_{y3u} - L_L F_{x3L} + L_L \mu F_{y3L}$$
$$= A_{41} + A_{42}\,\dot{\phi} \tag{D-184}$$

where

$$A_{41} = I_{ys}\,\dot{\omega}_y + \omega_x\,\omega_z\left(I_{xs} - I_{zs}\right) \tag{D-185}$$

$$A_{42} = - I_{zs}\,\omega_x \tag{D-186}$$

Z-Component of Moment Equation

For present purposes equation D-172 remains as it is.

Solution of Escape Wheel Pivot Forces. To derive expressions for the escape wheel pivot forces, equations D-173, D-177, D-181, and D-184 must be solved simultaneously. To obtain the same general form as in equation D-67, equations D-173 and D-177 are multiplied by (-1). The resulting form may then use the solution to equation D-67. Note that A_{11} in equation D-67 is now replaced by μ. Then,

$$\begin{bmatrix} -1 & \mu & 1 & -\mu \\ -\mu & -1 & \mu & 1 \\ \mu L_u & L_u & \mu L_L & L_L \\ -L_u & \mu L_u & -L_L & \mu L_L \end{bmatrix} \begin{bmatrix} F_{x3u} \\ F_{y3u} \\ F_{x3L} \\ F_{y3L} \end{bmatrix} = \begin{bmatrix} B_{s1} \\ B_{s2} \\ B_{s3} \\ B_{s4} \end{bmatrix} \tag{D-187}$$

where now:

$$B_{s1} = - [P_n A_{33} + F_{23} A_{34} + A_{35}] \tag{D-188}$$

$$B_{s2} = - [P_n A_{36} + F_{23} A_{37} + A_{38}] \tag{D-189}$$

$$B_{s3} = A_{39} + A_{40}\,\dot{\phi} \tag{D-190}$$

$$B_{s4} = A_{41} + A_{42}\,\dot{\phi} \tag{D-191}$$

Evaluation of the Coefficient Determinant D

The solution for the coefficient determinant D of equation D-187 is identical to equation D-72. With A_{11} now being equal to μ, the following parallel to equation D-75 is obtained:

$$D = [(L_u + L_L)(1 + \mu^2)]^2 \qquad \text{(D-192)}$$

Evaluation of Pivot Force $\tilde{F}_{x3u}$

The pivot force F_{x3u} is obtained from:

$$F_{x3u} = \frac{D_{F_{x3u}}}{D} \qquad \text{(D-193)}$$

where

$$D_{F_{x3u}} = \begin{vmatrix} B_{s1} & \mu & 1 & -\mu \\ B_{s2} & -1 & \mu & 1 \\ B_{s3} & L_u & \mu L_L & L_L \\ B_{s4} & \mu L_u & -L_L & \mu L_L \end{vmatrix} \qquad \text{(D-194)}$$

If μ is substituted for A_{11} in equation D-77, the identical form as above is obtained and the solution of equation D-80 can be adapted,

$$D_{F_{x3u}} = (1 + \mu^2)(L_u + L_L)[-L_L\ B_{s1} - \mu\ L_L\ B_{s2} + \mu\ B_{s3} - B_{s4}] \qquad \text{(D-195)}$$

Now equations D-188 to D-191 are substituted into the above expression and the coefficients of similar terms are collected. In order to get conservative pivot and pivot friction forces, the latter terms are made absolute. Finally, the tilded force $\tilde{F}_{x3u}$ is obtained from the appropriate change of equation D-193:

$$\tilde{F}_{x3u} = \frac{\tilde{D}_{F_{x3u}}}{D} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{21} + C_{22}\ P_n + C_{23}\ F_{23} + C_{24}\ \dot{\phi}] \qquad \text{(D-196)}$$

where

$$C_{21} = |L_L\ A_{35} - A_{41} + \mu\ (L_L\ A_{38} + A_{39})| \qquad \text{(D-197)}$$

$$C_{22} = |L_L\ (A_{33} + \mu\ A_{36})| \tag{D-198}$$

$$C_{23} = |L_L\ (A_{34} + \mu\ A_{37})| \tag{D-199}$$

$$C_{24} = |\mu\ A_{40} - A_{42}| \tag{D-200}$$

Evaluation of Pivot Force $\tilde{F}_{y3u}$

The pivot force F_{y3u} is obtained from:

$$F_{y3u} = \frac{D_{F_{y3u}}}{D} \tag{D-201}$$

where

$$D_{F_{y3u}} = \begin{vmatrix} -1 & B_{s1} & 1 & -\mu \\ -\mu & B_{s2} & \mu & 1 \\ \mu\ L_u & B_{s3} & \mu\ L_L & L_L \\ -L_u & B_{s4} & -L_L & \mu\ L_L \end{vmatrix} \tag{D202}$$

Since the form of the above is the same as that of the determinant of equation D-89, equation D-90, which represents the solution of the latter, may be adapted as follows:

$$D_{F_{y3u}} = (L_u + L_L)(1 + \mu^2)[\mu\ L_L\ B_{s1} - L_L\ B_{s2} + B_{s3} + \mu\ B_{s4}] \tag{D-202a}$$

Again, substitute the B_{si} terms of equations D-188 to D-191, collect the coefficients of similar terms, and make the result absolute. The tilded pivot force $\tilde{F}_{y3u}$ then becomes parallel to equation D-201:

$$\tilde{F}_{y3u} = \frac{\tilde{D}_{F_{y3u}}}{D} = \frac{1}{(L_u + L_L)(1 + \mu^2)}\ [C_{25} + C_{26}\ P_n + C_{27}\ F_{23} + C_{28}\ \dot{\phi}] \tag{D-203}$$

where

$$C_{25} = |L_L\ A_{38} + A_{39} + \mu\ (A_{41} - L_L\ A_{35})| \tag{D-204}$$

$$C_{26} = |L_L\ (A_{36} - \mu\ A_{33})| \tag{D-205}$$

$$C_{27} = |L_L\ (A_{37} - \mu\ A_{34})| \tag{D-206}$$

$$C_{28} = |A_{40} + \mu\ A_{42}| \tag{D-207}$$

<u>Evaluation of Pivot Force $\tilde{F}_{x3L}$</u>

The pivot force F_{x3L} is obtained from:

$$F_{x3L} = \frac{D_{F_{x3L}}}{D} \tag{D-208}$$

where

$$D_{F_{x3L}} = \begin{vmatrix} -1 & \mu & B_{s1} & -\mu \\ -\mu & -1 & B_{s2} & 1 \\ \mu\ L_u & L_u & B_{s3} & L_L \\ -L_u & \mu\ L_u & B_{s4} & \mu\ L_L \end{vmatrix} \tag{D-209}$$

Since the form of the above is the same as that of equation D-98, equation D-100 may be adapted, i.e.,

$$D_{F_{x3L}} = (L_u + L_L)(1 + \mu^2)[L_u\ B_{s1} + \mu\ L_u\ B_{s2} + \mu\ B_{s3} - B_{s4}] \tag{D-210}$$

Again, the B_{si} terms are substituted according to equations D-188 to D-191 and the requisite work obtains the tilded determinant $\tilde{D}_{F_{x3L}}$. Then,

$$\tilde{F}_{x3L} = \frac{\tilde{D}_{F_{x3L}}}{D} = \frac{1}{(L_u + L_L)(1 + \mu^2)}\ [C_{29} + C_{30}\ F_u + C_{31}\ F_{23} + C_{32}\ \dot{\phi}] \tag{D-211}$$

where

$$C_{29} = |\mu\ (A_{39} - L_u\ A_{38}) - L_u\ A_{35} - A_{41}| \tag{D-212}$$

$$C_{30} = |L_u\ (A_{33} + \mu\ A_{36})| \tag{D-213}$$

$$C_{31} = |L_u\ (A_{34} + \mu\ A_{37})| \tag{D-214}$$

$$C_{32} = |\mu\ A_{40} - A_{42}| \tag{D-215}$$

Evaluation of Pivot Force $\tilde{F}_{y3L}$

The pivot force F_{y3L} is obtained from

$$F_{y3L} = \frac{D_{F_{y3L}}}{D} \tag{D-216}$$

where

$$D_{F_{y3L}} = \begin{vmatrix} -1 & \mu & 1 & B_{s1} \\ -\mu & -1 & \mu & B_{s2} \\ \mu\ L_u & L_u & \mu\ L_L & B_{s3} \\ -L_u & \mu L_u & -L_L & B_{s4} \end{vmatrix} \tag{D-217}$$

Since the form of the above is the same as that of equation D-108, equation D-110 may be adapted to the present situation, therefore,

$$D_{F_{y3L}} = (L_u + L_L)(1 + \mu^2)\ \{-\mu\ L_u\ B_{s1} + L_u\ B_{s2} + B_{s3} + \mu\ B_{s4}\} \tag{D-218}$$

The B_{si} terms are now substituted according to equations D-188 to D-191, terms are collected and the tilded pivot force is defined:

$$\tilde{F}_{y3L} = \frac{\tilde{D}_{F_{y3L}}}{D} = \frac{1}{(L_u + L_L)(1 + \mu^2)}\ [C_{33} + C_{34}\ P_n + C_{35}\ F_{23} + C_{36}\ \dot{\phi}] \tag{D-219}$$

where

$$C_{33} = |\mu\ (A_{41} + L_u\ A_{35}) + A_{39} - L_u\ A_{38}| \tag{D-220}$$

$$C_{34} = |L_u\ (\mu\ A_{33} - A_{36})| \tag{D-221}$$

$$C_{35} = |L_u\ (\mu\ A_{34} - A_{37})| \tag{D-222}$$

$$C_{36} = |A_{40} + \mu\ A_{42}| \tag{D-223}$$

Substitution of Conservative (Tilded) Pivot Forces into the z-Component of the Moment Equation. Again, let the sum of the tilded pivot forces be first determined. Subsequently, this expression is substituted into the moment equation D-172. Then,

$$\tilde{F}_{x3u} + \tilde{F}_{y3u} + \tilde{F}_{x3L} + \tilde{F}_{y3L}$$

$$= A_{43} + A_{44} P_n + A_{45} F_{23} + A_{46} \dot{\phi} \tag{D-224}$$

where

$$L_T = L_u + L_L \tag{D-225}$$

$$A_{43} = \frac{C_{21} + C_{25} + C_{29} + C_{33}}{L_T (1 + \mu^2)} \tag{D-226}$$

$$A_{44} = \frac{C_{22} + C_{26} + C_{30} + C_{34}}{L_T (1 + \mu^2)} \tag{D-227}$$

$$A_{45} = \frac{C_{23} + C_{27} + C_{31} + C_{35}}{L_T (1 + \mu^2)} \tag{D-228}$$

$$A_{46} = \frac{C_{24} + C_{28} + C_{32} + C_{36}}{L_T (1 + \mu^2)} \tag{D-229}$$

Equation D-224 is now substituted into equation D-172. Further, F_{z3} of equation D-166 is made conservative, i.e.,

$$\tilde{F}_{z3} = A_{47} = |N_z m_3| \tag{D-230}$$

Equation D-172 then becomes:

$$- P_n (A_1' - B_1 \mu_1 s_4) + F_{23} [r_{b3} - \mu s_2 (d_2 - a_2)]$$

$$-\mu \rho_{f3} A_{47} - \mu \rho_3 [A_{43} + A_{44} P_n + A_{45} F_{23} + A_{46} \dot{\phi}]$$

$$= I_{zs} \dot{\omega}_z + I_{zs} \ddot{\phi} \tag{D-231}$$

The above expression must now be solved for P_n. Before this is possible, consider the sign of the friction moment component:

$$-\mu\ \rho_3\ A_{46}\ \dot{\phi} \qquad \text{(D-232)}$$

Since a reversal of gear train motion after impact will again be expressed by letting μ become negative, as described originally in appendix E of reference 4, equation D-232 is modified to read:

$$-\ \mu\ \rho_3\ A_{46}\ \frac{\dot{\phi}^2}{|\dot{\phi}|} \qquad \text{(D-233)}$$

In this way, the sign of μ alone decides the direction of this friction torque component. P_n is then obtained from equation D-172:

$$\begin{aligned} &P_n\ \left[-\ A_1' + B_1'\ \mu_1 s_4 - \mu\ \rho_3\ A_{44}\right] \\ &+ F_{23}\ \left[r_{b3} - \mu\ s_2\ (d_2 - a_2) - \mu\ \rho_3\ A_{45}\right] \\ &-\ \mu\ \rho_3\ A_{46}\ \frac{\dot{\phi}^2}{|\dot{\phi}|} - \mu\ \left[\rho_{f3}\ A_{47} + \rho_3\ A_{43}\right] \\ &= I_{zs}\ \ddot{\phi} + I_{zs}\ \dot{\omega}_z \end{aligned} \qquad \text{(D-234)}$$

Then

$$P_n = \frac{I_{zs}\ \ddot{\phi} + A_{48}\ \dot{\phi}^2 + F_{23}\ A_{49} + A_{50}}{A_{51}} \qquad \text{(D-235)}$$

where

$$A_{48} = \frac{\mu\ \rho_3\ A_{46}}{|\dot{\phi}|} \qquad \text{(D-236)}$$

$$A_{49} = \mu\ \left[s_2\ (d_2 - a_2) + \rho_3\ A_{45}\right] - r_{b3} \qquad \text{(D-237)}$$

$$A_{50} = I_{zs}\ \dot{\omega}_z + \mu\ \left[\rho_{f3}\ A_{47} + \rho_3\ A_{43}\right] \qquad \text{(D-238)}$$

$$A_{51} = B_1'\ \mu_1 s_4 - A_1' - \mu\ \rho_3\ A_{44} \qquad \text{(D-239)}$$

<u>Combined Entrance Coupled Motion Differential Equation</u>. Equations D-140 and D-235 are now set equal to each other. This furnishes the following combined

coupled motion differential equation for the escapement under entrance conditions:

$$[A_{51} I_{PR} U - A_{29} I_{zs}] \ddot{\phi} + [A_{51} (A_{32} U^2 + I_{PR} V) - A_{29} A_{48}] \dot{\phi}^2$$

$$+ A_{51} A_{31} U \dot{\phi} = F_{23} A_{29} A_{49} + A_{29} A_{50} - A_{51} (A_9 + A_{30})$$

$$+ A_{51} m_p r_{cp} (K_x \sin \beta - K_y \cos \beta) \tag{D-240}$$

Pallet and Escapement Wheel in Exit Coupled Motion

Pallet Equations. The free body diagram of the pallet for exit coupled motion is given by figures D-5a and D-5b. Now

$$\bar{P}_n = - P_n \bar{n}_n \tag{D-241}$$

This sign change will be reflected both in the force and in the moment expressions. The following shows the relevant changes in equations D-23 and D-140:

Changes in Force Equations of Pallet

Equation D-24 is modified to accommodate equation D-241. The associated friction forces have their directions determined by the signum functions s_4 and s_5, as before. Therefore, equation D-24 is changed in its first term only:

$$-P_n \bar{n}_n + \mu_1 s_4 P_n \bar{n}_t + \dots\dots\dots \tag{D-242}$$

With the unit vectors of equations D-25 and D-26, the x'-force equation D-27 is modified to:

$$P_n \sin (\psi + \alpha) + \mu_1 s_4 P_n \cos (\psi + \alpha) - F_{x'u} - \mu_1 s_5 F_{y'u}$$

$$+ F_{x'L} + \dots\dots \tag{D-243}$$

The terms in the y'-expression D-28 are changed as follows:

$$- P_n \cos (\psi + \alpha) + \mu_1 s_4 P_n \sin (\psi + \alpha) - F_{y'u} - \mu_1 s_5 F_{x'u}$$

$$+ F_{y'L} + \dots\dots \tag{D-244}$$

The expression for $F_{z'}$ remains as given by equation D-29.

Changes in Moment Equation of Pallet

The form of P_n, according to equation D-241, also reflects itself in the expression for $\bar{M}_{0p}$ (eq D-61). Therefore, for the exit case

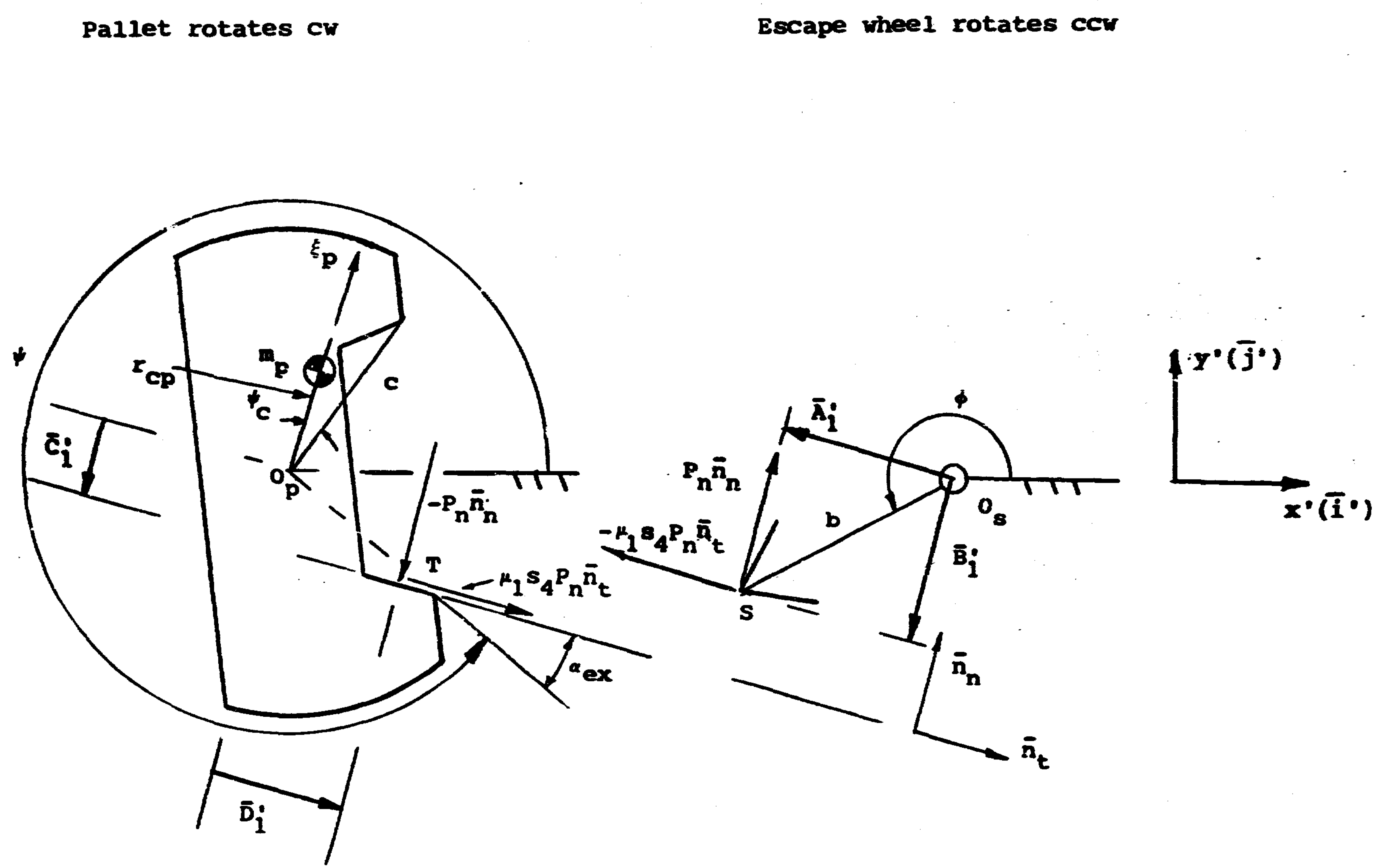


Figure D-5a. Top view free body diagram of pallet in exit coupled motion

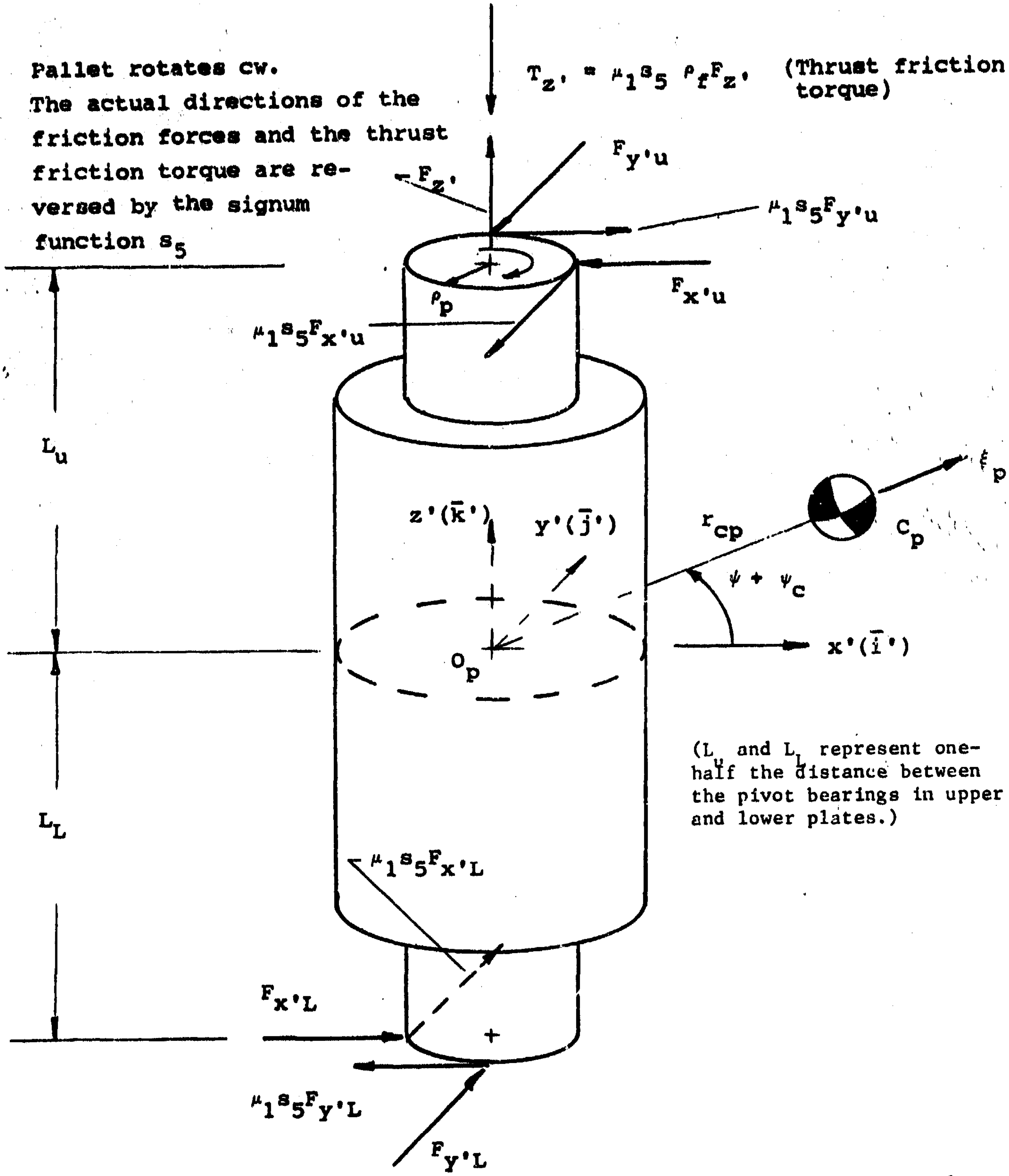


Figure D-5b. Pallet in exit coupled motion. Normal forces, friction forces, and thrust friction torque acting on pallet pivots.

$$\bar{M}_{O_p} = - D_1 P_n \bar{k}' - \mu_1 s_4 C_1 P_n \bar{k}' \; . \; . \; . \; . \; . \qquad (D\text{-}245)$$

Simplification of Force and Moment Equations.

x'-Force Component

Due to the change shown in equation D-243, the parameter A_{16} in equation D-48 must be changed to become:

$$AA_{16} = -\left[\mu_1 s_4 \cos(\psi + \alpha) + \sin(\psi + \alpha)\right] \qquad (D\text{-}246)$$

y'-Force Component

Similarly, because of the change in equation D-244, the parameter A_{21} in equation D-55 must be changed to:

$$AA_{21} = -\left[\mu_1 s_4 \sin(\psi + \alpha) - \cos(\psi + \alpha)\right] \qquad (D\text{-}247)$$

z'-Force Component

The z'-force component remains as that given by equation D-61, as stated earlier.

x'- and y'-Moment Component Equations

The x'- and y'-moment component equations remain unchanged from equations D-64 and D-65, respectively, since they do not contain P_n.

z'-Moment Component Equation

Because of the changes shown in equation D-245, the z'-moment component expression D-66 must now be modified to read:

$$- P_n \left(D_1' + \mu_1 s_4 C_1'\right) - \rho_f A_{11} F_{z'} - \rho_p A_{11} F_{y'u} - \rho_p A_{11} F_{x'u}$$

$$- \rho_p A_{11} F_{y'L} - \rho_p A_{11} F_{x'L}$$

$$= - m_p r_{cp} \left(K_x \sin\beta - K_y \cos\beta\right) + A_9 + A_{10} \ddot{\psi} \qquad (D\text{-}248)$$

Solution of Pallet Pivot Forces. The solution for the pivot forces $F_{x'u}$, $F_{y'u}$, $F_{x'L}$, and $F_{y'L}$ is identical to that shown for the entrance coupled motion, keeping in mind that now the parameters AA_{16} and AA_{21} are used instead of A_{16} and A_{21}. Equation D-117 must subsequently be changed to:

$$\tilde{F}_{x'u} + \tilde{F}_{y'u} + \tilde{F}_{x'L} + \tilde{F}_{y'L} =$$

$$A_{24} + \dot{\psi} A_{25} + \dot{\psi}^2 A_{26} + \ddot{\psi} A_{27} + P_n AA_{28} \qquad \text{(D-249)}$$

A_{24} to A_{27} remain the same; so does AA_{28} as long as it is realized that it contains AA_{16} and AA_{21}.

Substitution of Pallet Pivot Forces into z'-Moment Component Equation: Determination of P_n. Because of the changes in equation D-248, and using the same reasoning as employed for equations D-123 to D-128, equation D-128 becomes for exit coupled motion:

$$P_n AA_{29} - A_{30} - A_{31} \dot{\psi} - A_{32} \dot{\psi}^2$$

$$= I_{PR} \ddot{\psi} + A_9 - m_p r_{cp} (K_x \sin \beta - K_y \cos \beta) \qquad \text{(D-250)}$$

where

$$AA_{29} = - \left[D_1' + C_1' \mu_1 s_4 + \rho_p \mu_1 s_5 AA_{28}\right] \qquad \text{(D-251)}$$

Finally, parallel to equation D-137, the contact force P_n becomes:

$$P_n = \frac{I_{PR} \ddot{\psi} + A_9 + A_{30} + A_{31} \dot{\psi} + A_{32} \dot{\psi}^2 - m_p r_{cp} (K_x \sin \beta - K_y \cos \beta)}{AA_{29}} \qquad \text{(D-252)}$$

If this expression is rewritten in terms of the escape wheel variables $\dot{\phi}$ and $\ddot{\phi}$ the following equation which is similar to equation D-140 is obtained:

$$P_n = \frac{1}{AA_{29}} [I_{PR} U \ddot{\phi} + (A_{32} U^2 + I_{PR} V) \dot{\phi}^2$$

$$+ A_{31} U \dot{\phi} + A_9 + A_{30} - m_p r_{cp} (K_x \sin \beta - K_y \cos \beta)] \qquad \text{(D-253)}$$

Escape Wheel Equations. The free body diagram of the escape wheel in exit coupled motion is given in figures D-6a and D-6b. The change in the contact force P_n must again be accounted for.

Escape Wheel rotates ccw

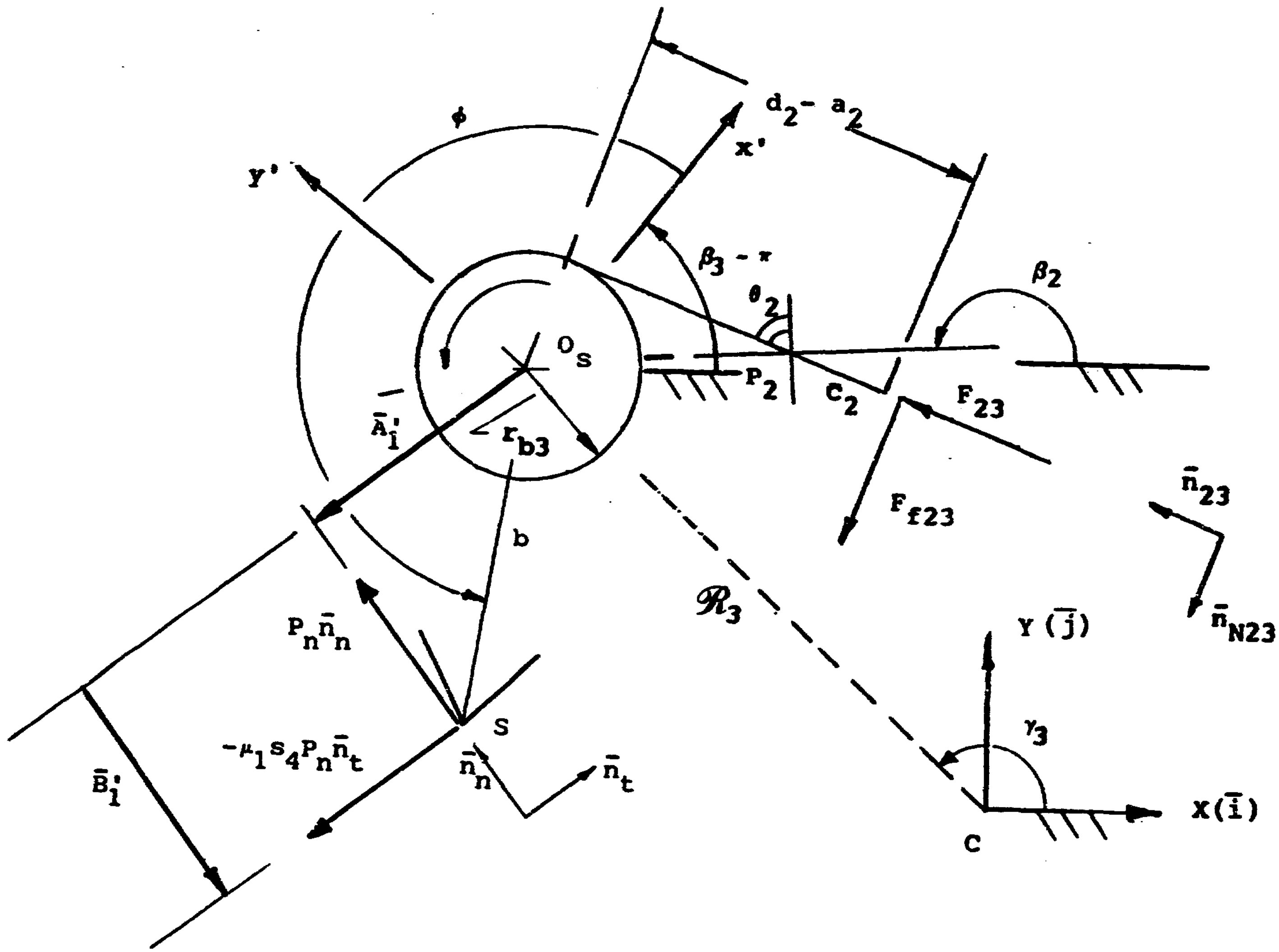


Figure D-6a. Top view free body diagram of escape wheel and pinion no. 3 in exit coupled motion

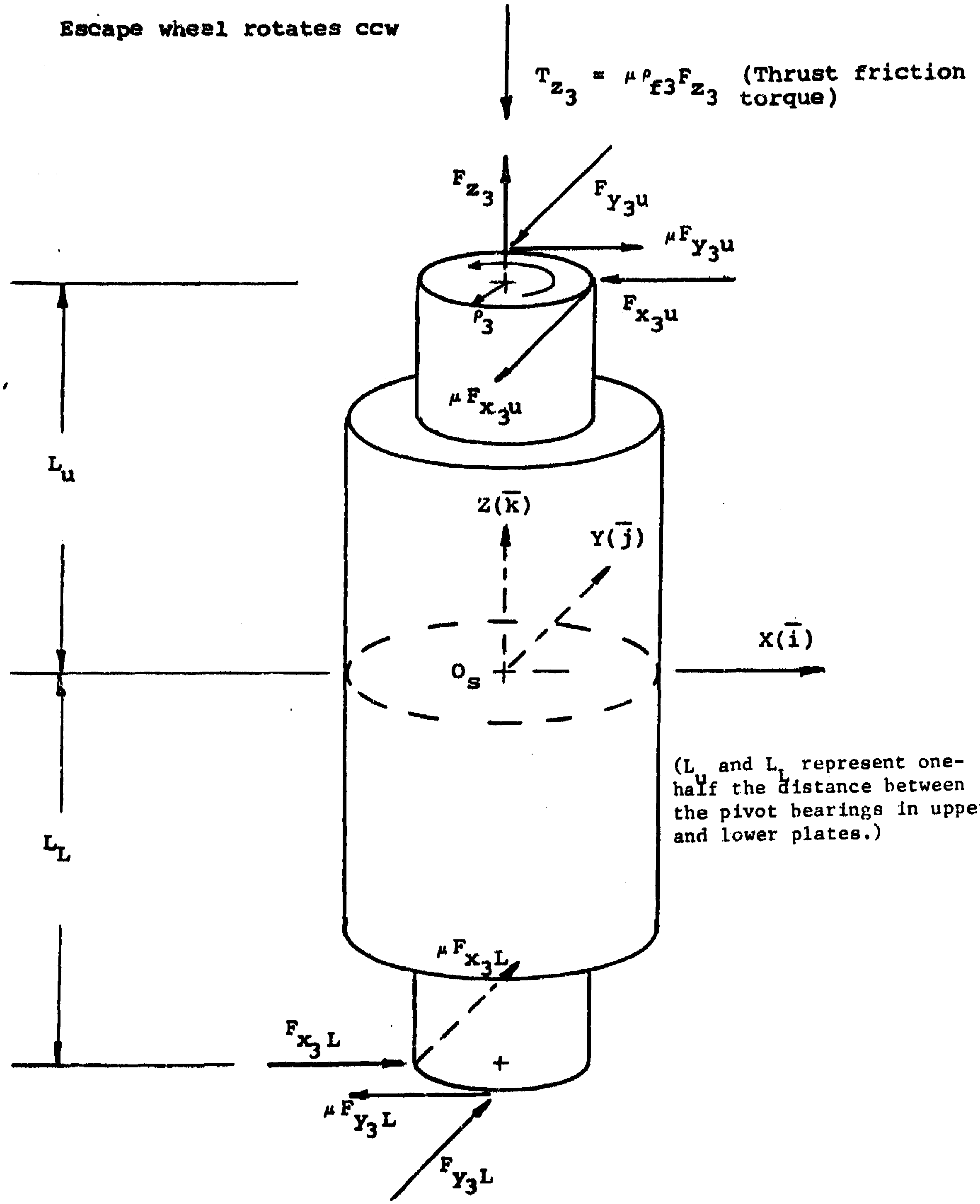


Figure D-6b. Escape wheel and pinion no. 3 in exit coupled motion. Normal forces, friction forces, and thrust friction torque acting on escape wheel pivots.

Changes in Force Equations of Escape Wheel

Equation D-161 must be modified to read:

$$P_n \bar{n}_n - \mu_1 s_4 P_n \bar{n}_t + F_{23} \bar{n}_{23} + \cdot\cdot\cdot\cdot\cdot \tag{D-254}$$

With the unit vectors of equations D-143 and D-144, the X-force component equation (changed from equation D-164) becomes:

$$\begin{aligned} &P_n \sin(\psi + \alpha + \beta_3) + \mu_1 s_4 P_n \cos(\psi + \alpha + \beta_3) \\ &+ F_{23} \sin(\beta_2 + \theta_2) + \mu s_2 F_{23} \cos(\beta_2 + \theta_2) - F_{x3u} \\ &+ \mu F_{y3u} + F_{x3L} - \mu F_{y3L} = N_x m_3 \end{aligned} \tag{D-255}$$

The Y-force component is changed from equation D-165 to read:

$$\begin{aligned} &- P_n \cos(\psi + \alpha + \beta_3) + \mu_1 s_4 P_n \sin(\psi + \alpha + \beta_3) \\ &- F_{23} \cos(\beta_2 + \theta_2) + \mu s_2 F_{23} \sin(\beta_2 + \theta_2) - F_{y3u} \\ &- \mu F_{x3u} + F_{y3L} + \mu F_{x3L} = N_y m_3 \end{aligned} \tag{D-256}$$

The Z-force component remains as in equation D-166, i.e.,

$$F_{z3} = N_3 m_3 \tag{D-257}$$

Changes in Moment Equations of Escape Wheel

The moment equation D-167 for the escape wheel and pinion no. 3 must also reflect the change in P_n. The left-hand side of the above expression, as given by equation D-168 must be modified, because now the cross product

$$A_1 \bar{n}_t \times P_n \bar{n}_n = P_n A_1' \bar{k} \tag{D-258}$$

This results in the following change to equation D-168

$$P_n (A_1' + B_1' \mu_1 s_4) \bar{k} + r_{b3} F_{23} \bar{k} - \cdot\cdot\cdot\cdot\cdot \tag{D-259}$$

The right-hand side of equation D-167 remains unchanged. The resulting X and Y moment component expressions, i.e., equations D-170 and D-171, respectively, are

not influenced by the above change. The Z-moment component expression D-172 must now read:

$$P_n \left(A_1' + B_1' \mu_1 s_4\right) + F_{23} \left[r_{b3} - \mu s_2 \left(d_2 - a_2\right)\right] - \ldots\ldots \qquad \text{(D-260)}$$

Simplification of New Force and Moment Equations of Escape Wheel.

X-Force Component

Due to the change in equation D-255, the parameter A_{33} in equation D-173 must be changed to

$$AA_{33} = \mu_1 s_4 \cos\left(\psi + \alpha + \beta_3\right) + \sin\left(\psi + \alpha + \beta_3\right) \qquad \text{(D-261)}$$

Y-Force Component

Similarly, because of the change in equation D-256, the parameter A_{36} in equation D-177 now becomes:

$$AA_{36} = \mu_1 s_4 \sin\left(\psi + \alpha + \beta_3\right) - \cos\left(\psi + \alpha + \beta_3\right) \qquad \text{(D-262)}$$

Z-Force Component

The Z-force component remains presently as given by equation D-257.

As stated earlier, the X- and Y-components of the moment expressions for the escape wheel need not be changed. They are used in their final form as given by equations D-181 and D-184, respectively. Therefore, the X-component of the moment equation is given by:

$$\mu L_u F_{x3u} + L_u F_{y3u} + \mu L_L F_{x3L} + L_L F_{y3L}$$
$$= A_{39} + A_{40} \dot{\phi} \qquad \text{(D-263)}$$

The Y-component of the moment equation is

$$- L_u F_{x3u} + L_u \mu F_{y3u} - L_L F_{x3L} + L_L \mu F_{y3L}$$
$$= A_{41} + A_{42} \dot{\phi} \qquad \text{(D-264)}$$

<u>Solution of Escape Wheel Pivot Forces for Exit Coupled Motion</u>. Since only the parameters AA_{33} and AA_{36} differ in the set of simultaneous equations D-173, D-177, D-263, and D-264 from those used in the solution for the pivot forces in entrance coupled motion, the latter is adapted to the present situation. Then, according to equation D-196

$$\tilde{F}_{x3u} = \frac{1}{(L_u + L_L)(1 + \mu^2)} \left[C_{21} + CC_{22} P_n + C_{23} F_{23} + C_{24} \dot{\phi}\right] \qquad \text{(D-265a)}$$

where, now

$$CC_{22} = |L_L (AA_{33} + \mu AA_{36})| \qquad \text{(D-265b)}$$

and, as before

$$C_{21} = |L_L A_{35} - A_{41} + \mu (L_L A_{38} + A_{39})|$$

$$C_{23} = |L_L (A_{34} + \mu A_{37})|$$

$$C_{24} = |\mu A_{40} - A_{42}|$$

According to equation D-204:

$$\tilde{F}_{y3u} = \frac{1}{(L_u + L_L)(1 + \mu^2)} \left[C_{25} + CC_{26} P_n + C_{27} F_{23} + C_{28} \dot{\phi}\right] \qquad \text{(D-266)}$$

where now,

$$CC_{26} = |L_L (AA_{36} - \mu AA_{33})| \qquad \text{(D-267)}$$

and, as before

$$C_{25} = |L_L A_{38} + A_{39} + \mu (A_{41} - L_L A_{35})|$$

$$C_{27} = |L_L (A_{37} - \mu A_{34})|$$

$$C_{28} = |A_{40} + \mu A_{42}|$$

According to equation D-212:

$$\tilde{F}_{x3L} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{29} + CC_{30} P_n + C_{31} F_{23} + C_{32} \dot{\phi}] \qquad \text{(D-268)}$$

where now,

$$CC_{30} = | L_u (AA_{33} + \mu AA_{36})| \qquad \text{(D-269)}$$

and as before

$$C_{29} = |\mu (A_{39} - L_u A_{38}) - L_u A_{35} - A_{41}|$$

$$C_{31} = |L_u (A_{34} + \mu A_{37})|$$

$$C_{32} = |\mu A_{40} - A_{42}|$$

According to equation D-219:

$$\tilde{F}_{y3L} = \frac{1}{(L_u + L_L)(1 + \mu^2)} [C_{33} + CC_{34} P_n + C_{35} F_{23} + C_{36} \dot{\phi}] \qquad \text{(D-270)}$$

where now,

$$CC_{34} = |L_u (\mu AA_{33} - AA_{36})| \qquad \text{(D-271)}$$

and, as before

$$C_{33} = |\mu (A_{41} + L_u A_{35}) + A_{39} - L_u A_{38}|$$

$$C_{35} = |L_u (\mu A_{34} - A_{37})|$$

$$C_{36} = |A_{40} + \mu A_{42}|$$

Substitution of Conservative (Tilded) Pivot Forces into Z-Moment Expression. The sum of the tilded pivot forces is identical in form to equation D-224. Therefore, with equations D-265, D-266, D-268, and D-270, the following is obtained:

$$\tilde{F}_{x3u} + \tilde{F}_{y3u} + \tilde{F}_{x3L} + \tilde{F}_{y3L}$$

$$= A_{43} + AA_{44}\, P_n + A_{45}\, F_{23} + A_{46}\, \dot{\phi} \tag{D-272}$$

where now,

$$AA_{44} + \frac{CC_{22} + CC_{26} + CC_{30} + CC_{34}}{L_T\,(1 + \mu^2)} \tag{D-273}$$

and, as before

$$A_{43} = \frac{C_{21} + C_{25} + C_{29} + C_{33}}{L_T\,(1 + \mu^2)}$$

$$A_{45} = \frac{C_{23} + C_{27} + C_{31} + C_{35}}{L_T\,(1 + \mu^2)}$$

$$A_{46} = \frac{C_{24} + C_{28} + C_{32} + C_{36}}{L_T\,(1 + \mu^2)}$$

Substitution of equations D-257 and D-272 into equation D-260 furnishes the complete Z-component of the escape wheel moment expression for exit coupled motion:

$$P_n\,(A_1' + B_1'\mu_1 s_4) + F_{23}\,[r_{b3} - \mu\, s_2\,(d_2 - a_2)] - \mu\,\rho_{f3}\,A_{47}$$

$$- \mu\,\rho_3\,[A_{43} + AA_{44}\,P_n + A_{45}\,F_{23} + A_{46}\,\dot{\phi}] = I_{zs}\,\dot{\omega}_z + I_{zs}\,\ddot{\phi} \tag{D-274}$$

Using the same reasoning as given in connection with equations D-232 and D-233, equation D-274 now solved for P_n. Therefore,

$$P_n\,[A_1' + B_1'\,\mu_1 s_4 - \mu\,\rho_3\,AA_{44}]$$

$$+ F_{23}\,[r_{b3} - \mu\,s_2\,(d_2 - a_2) - \mu\,\rho_3\,A_{45}]$$

$$- \mu\,\rho_3\,A_{46}\,\frac{\dot{\phi}^2}{|\dot{\phi}|} - \mu\,[\rho_{f3}\,A_{47} + \rho_3\,A_{43}] = I_{zs}\,\ddot{\phi} + I_{zs}\,\dot{\omega}_z \tag{D-275}$$

and, similar to equation D-235

$$P_n = \frac{I_{zs}\ \ddot{\phi} + A_{48}\ \dot{\phi}^2 + F_{23}\ A_{49} + A_{50}}{AA_{51}} \tag{D-276}$$

where now

$$AA_{51} = A_1' + B_1'\ \mu_1 s_4 - \mu\ \rho_3\ AA_{44} \tag{D-277}$$

while as before,

$$A_{48} = \frac{\mu\ \rho_3\ A_{46}}{|\dot{\phi}|}$$

$$A_{49} = \mu\ [s_2\ (d_2 - a_2) + \rho_3\ A_{45}] - r_{b3}$$

$$A_{50} = I_{zs}\ \dot{\omega}_z + \mu\ [\rho_{f3}\ A_{47} + \rho_3\ A_{43}]$$

Combined Exit Coupled Motion Differential Equation. Equations D-253 and D-276 are now set equal to each other in order to obtain the combined coupled motion differential equation of the escapement under exit conditions:

$$\begin{aligned} &[AA_{51}\ I_{PR}\ U - AA_{29}\ I_{zs}]\ \ddot{\phi} + [AA_{51}\ (A_{32}\ U^2 + I_{PR}\ V) \\ &- AA_{29}\ A_{48}]\ \dot{\phi}^2 + AA_{51}\ A_{31}\ U\ \dot{\phi} \\ &\quad = F_{23}\ AA_{29}\ A_{49} + AA_{29}\ A_{50} - AA_{51}\ (A_9 + A_{30}) \\ &\quad\ + AA_{51}\ m_p\ r_{cp}\ (K_x \sin\beta - K_y \cos\beta) \end{aligned} \tag{D-278}$$

The above expression has the same form as equation D-240, and the difference between entrance and exit coupled depends on the value of the signum function s_7 which is introduced in the next section.

Common Expressions for Entrance- and Exit-Coupled Motion

It is possible to obtain common expressions for all the A's and C's (i.e., AA's and CC's) associated with entrance-and exit-coupled motion, if the signum functions s_7 are introduced, where

s_7 = positive for entrance-coupled motion

s_7 = negative for exit-coupled motion

With the above, equations D-54 and D-246 are satisfied, if

$$A_{16} = -\left[\mu_1 s_4 \cos(\psi + \alpha) - s_7 \sin(\psi + \alpha)\right] \qquad \text{(D-279a)}$$

Equations D-60 and D-247 are satisfied, if

$$A_{21} = -\left[s_7 \cos(\psi + \alpha) + \mu_1 s_4 \sin(\psi + \alpha)\right] \qquad \text{(D-279b)}$$

Equations D-130 and D-251 are satisfied, if

$$A_{29} = s_7 D_1' - C_1' \mu_1 s_4 - \rho_p \mu_1 s_5 A_{28} \qquad \text{(D-280)}$$

Equations D-174 and D-261 are satisfied, if

$$A_{33} = \mu_1 s_4 \cos\left(\psi + \alpha + \beta_3\right) - s_7 \sin\left(\psi + \alpha + \beta_3\right) \qquad \text{(D-281)}$$

Equations D-178 and D-262 are satisfied, if

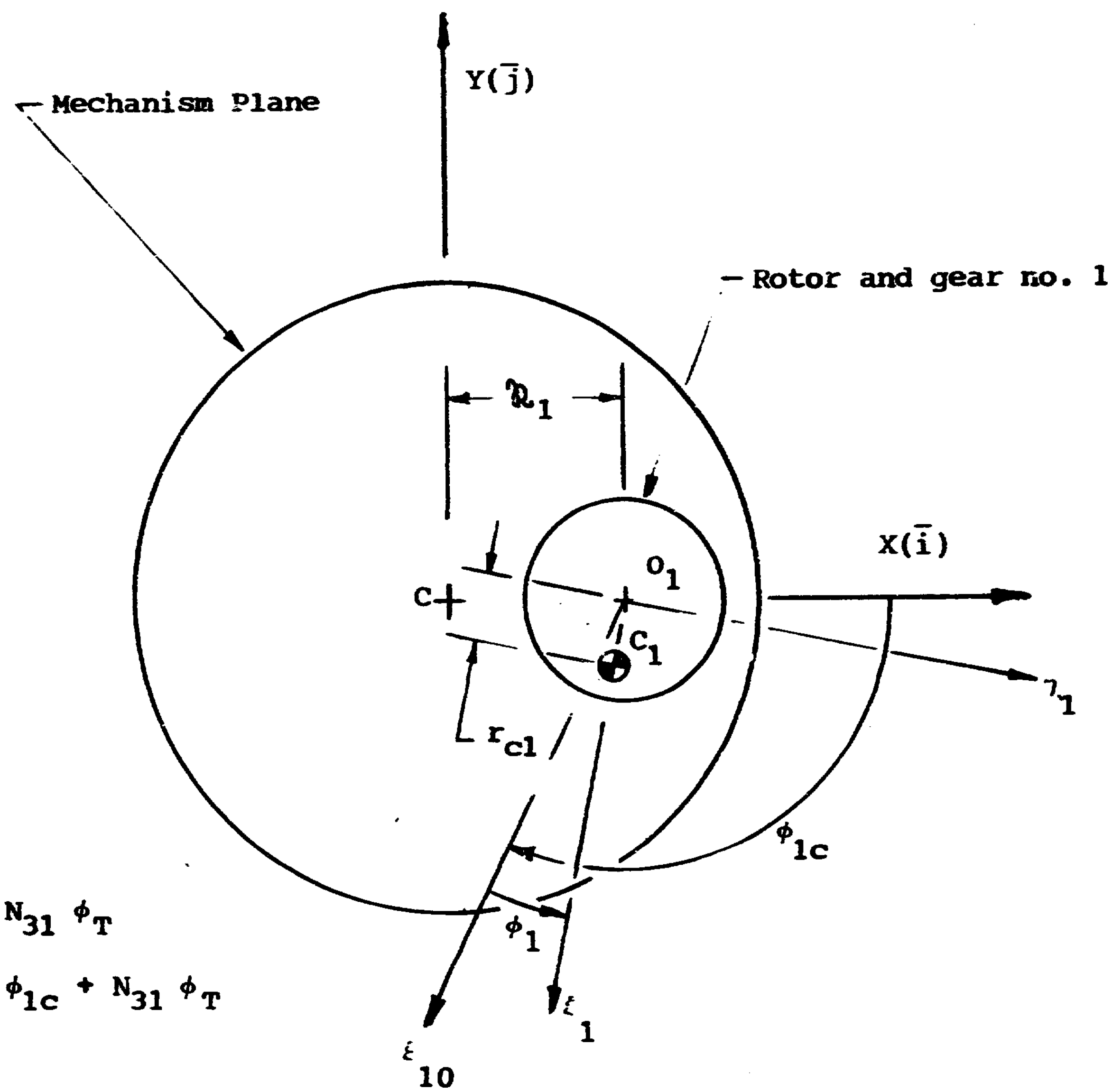
$$A_{36} = \mu_1 s_4 \sin\left(\psi + \alpha + \beta_3\right) + s_7 \cos\left(\psi + \alpha + \beta_3\right) \qquad \text{(D-282)}$$

Finally, equations D-239 and D-277 are satisfied, if

$$A_{51} = B_1' \mu_1 s_4 - s_7 A_1' - \mu \rho_3 A_{44} \qquad \text{(D-283)}$$

Dynamics of Rotor

Before the force and moment equations for the rotor can be considered, it is first necessary to obtain expressions for the absolute accelerations of the rotor pivot O_1 and the rotor center of mass C_1. A top view of the rotor in the mechanism plane is shown in figure D-7 (also fig. A-3).



Note: $\phi_1 = N_{31}\,\phi_T$

and $\gamma = \phi_{1c} + N_{31}\,\phi_T$

Figure D-7. Top view of rotor and gear no. 1 and mechanism plane

Absolute Acceleration of Rotor Pivot O_1

The absolute acceleration of the rotor pivot O_1 is given by

$$\bar{A}_{O_1/\text{ground}} = \bar{A}_{O_1/C} + \bar{A}_{C/\text{ground}} \tag{D-284}$$

where

$\bar{A}_{C/\text{ground}}$ = given by equation C-4 of appendix C in the projectile fixed X-Y system,

while

$$\bar{A}_{O_1/C} = \bar{\omega} \times (\bar{\omega} \times \bar{\mathcal{R}}_1) + \bar{\dot{\omega}} \times \bar{\mathcal{R}}_1 \tag{D-285}$$

After substituting

$$\bar{\mathcal{R}}_1 = \mathcal{R}_1 \, \bar{i} \tag{D-286}$$

and equations A-1 and A-5 for $\bar{\omega}$ and $\bar{\dot{\omega}}$, respectively, the following is obtained:

$$\bar{A}_{O_1/C} = L_x \, \bar{i} + L_y \, \bar{j} + L_z \, \bar{k} \tag{D-287}$$

where

$$L_x = -(\omega_y^{\ 2} + \omega_z^{\ 2}) \, \mathcal{R}_1 \tag{D-288}$$

$$L_y = (\omega_x \, \omega_y + \dot{\omega}_z) \, \mathcal{R}_1 \tag{D-289}$$

$$L_z = (\omega_x \, \omega_z - \dot{\omega}_y) \, \mathcal{R}_1 \tag{D-290}$$

Together with equations D-187 and C-4, the following is obtained for equation D-284:

$$\bar{A}_{O_1/\text{ground}} = O_x \, \bar{i} + O_y \, \bar{j} + O_z \, \bar{k} \tag{D-291}$$

where

$$O_x = G_x + L_x \tag{D-292}$$

$$O_y = G_y + L_y \tag{D-293}$$

$$O_z = G_z + L_z \tag{D-294}$$

Absolute Acceleration of the Rotor Center of Mass C_1

To determine the absolute acceleration of the rotor center of mass in the X-Y-Z system, it is first necessary to find $\bar{A}_{C_1/O_1}$, the acceleration of the rotor center of mass with respect to the rotor pivot O_1, in the $\xi_1 - \eta_1 - \zeta_1$ system (fig. B-7). Subsequently, this expression is transformed into the X-Y-Z system and added to the absolute acceleration of point O_1 as given by equation D-291. Therefore,

$$\bar{A}_{C_1/\text{ground}} = \bar{A}_{C_1/O_1} + \bar{A}_{O_1/\text{ground}} \tag{D-295}$$

The term $\bar{A}_{C_1/O_1}$ is obtained from:

$$\bar{A}_{C_1/O_1} = \bar{\omega}_1 \times (\bar{\omega}_1 \times \bar{r}_{c1}) + \bar{\dot{\omega}}_1 \times \bar{r}_{c1} \tag{D-296}$$

where

$$\bar{r}_{c1} = r_{c1}\,\bar{n}_{\xi_1} \tag{D-297}$$

The terms $\bar{\omega}_1$ and $\bar{\dot{\omega}}_1$ are taken from equations A-35 and A-39, respectively.

When all operations are performed, equation D-296 becomes:

$$\begin{aligned} \bar{A}_{C_1/O_1} = &- r_{c1}\,[\omega_{\eta_1}^2 + \omega_{\zeta_1}^2]\,\bar{n}_{\xi_1} \\ &+ r_{c1}\,[\omega_{\xi_1}\,\omega_{\eta_1} + \dot{\omega}_{\zeta_1}]\,\bar{n}_{\eta_1} \\ &+ r_{c1}\,[\omega_{\xi_1}\,\omega_{\zeta_1} - \dot{\omega}_{\eta_1}]\,\bar{n}_{\zeta_1} \end{aligned} \tag{D-298}$$

With the help of equations A-28 and A-31b substitute for the above body-fixed unit vectors; i.e.,

$$\bar{n}_{\xi_1} = \cos\gamma\,\bar{i} + \sin\gamma\,\bar{j} \tag{D-299}$$

$$\bar{n}_{\eta_1} = -\sin\gamma\,\bar{i} + \cos\gamma\,\bar{j} \tag{D-300}$$

$$\bar{n}_{\zeta_1} = \bar{k} \tag{D-301}$$

where

$$\gamma = \phi_{1c} + N_{31}\,\phi_T \tag{D-302}$$

This results in

$$\begin{aligned}\bar{A}_{C_1/O_1} = &- r_{c1}\,[(\omega_{\eta_1}^2 + \omega_{\zeta_1}^2)\cos\gamma + (\omega_{\xi_1}\,\omega_{\eta_1} + \dot{\omega}_{\zeta_1})\sin\gamma]\,\bar{i} \\ &- r_{c1}\,[(\omega_{\eta_1}^2 + \omega_{\zeta_1}^2)\sin\gamma - (\omega_{\xi_1}\,\omega_{\eta_1} + \dot{\omega}_{\zeta_1})\cos\gamma]\,\bar{j} \\ &+ r_{c1}\,[\omega_{\xi_1}\,\omega_{\zeta_1} - \dot{\omega}_{\eta_1}]\,\bar{k}\end{aligned} \tag{D-303}$$

Finally, equations A-36 to A-38 and A-40 to A-42 are used to express the angular quantities:

$$\begin{aligned}\bar{A}_{C_1/O_1} = - r_{c1}\,\{&[\omega_y^2\cos\gamma - \omega_x\,\omega_y\sin\gamma + (\omega_z + N_{31}\dot{\phi})^2\cos\gamma \\ &+ (\dot{\omega}_z + N_{31}\,\ddot{\phi})\sin\gamma]\,\bar{i} \\ &+ [\omega_x^2\sin\gamma - \omega_x\,\omega_y\cos\gamma + (\omega_z + N_{31}\,\dot{\phi})^2\sin\gamma \\ &- (\dot{\omega}_z + N_{31}\,\ddot{\phi})\cos\gamma]\,\bar{j} \\ &- [(\omega_x\cos\gamma + \omega_y\sin\gamma)(\omega_z + 2\,\dot{\phi}\,N_{31}) + \dot{\omega}_x\sin\gamma \\ &- \dot{\omega}_y\cos\gamma]\,\bar{k}\}\end{aligned} \tag{D-304}$$

The total acceleration $\bar{A}_{C_1/\text{ground}}$ then becomes according to equation D-295 with equation D-291:

$$\bar{A}_{C_1/ground} = \{ - r_{c1} \; [\omega_y^{\,2} \cos\gamma - \omega_x \, \omega_y \sin\gamma + (\omega_z + N_{31} \, \dot{\phi})^2 \cos\gamma$$

$$+ (\dot{\omega} + N_{31} \, \ddot{\phi}) \sin\gamma] + 0_x\} \, \bar{i}$$

$$+ \{- r_{c1} \; [\omega_x^{\,2} \sin\gamma - \omega_x \omega_y \cos\gamma + (\omega_z + N_{31} \, \dot{\phi})^2 \sin\gamma$$

$$- (\dot{\omega}_z + N_{31} \, \ddot{\phi}) \cos\gamma] + 0_y\} \, \bar{j}$$

$$+ \{r_{c1} \; [(\omega_x \cos\gamma + \omega_y \sin\gamma)(\omega_z + 2 \, N_{31} \, \dot{\phi})$$

$$+ \dot{\omega}_x \sin\gamma - \dot{\omega}_y \cos\gamma] + 0_z\} \, \bar{k} \qquad \text{(D-305)}$$

Force Equations for the Rotor

A top view of the rotor together with the mechanism plane is shown in figure D-8a. It indicates all required geometry, the base circle radius R_{b1}, and the contact force $\bar{F}_{21}$ as well as the associated friction force F_{f21} (for details, see refs 1, 2, and 4). A free body diagram of the rotor pivot with all normal and friction pivot forces is shown in figure D-8b.

The force equation for the rotor is given by:

$$\Sigma \, \bar{F} = m_1 \, \bar{A}_{C_1/ground} \qquad \text{(D-306)}$$

where $\bar{A}_{C1/ground}$ is given by equation D-305. Therefore

$$-F_{12} \, \bar{n}_{12} + \mu \, s_1 \, F_{12} \, \bar{n}_{N12} + F_{z1} \, \bar{k} - F_{x1u} \, \bar{i} - F_{y1u} \, \bar{j}$$

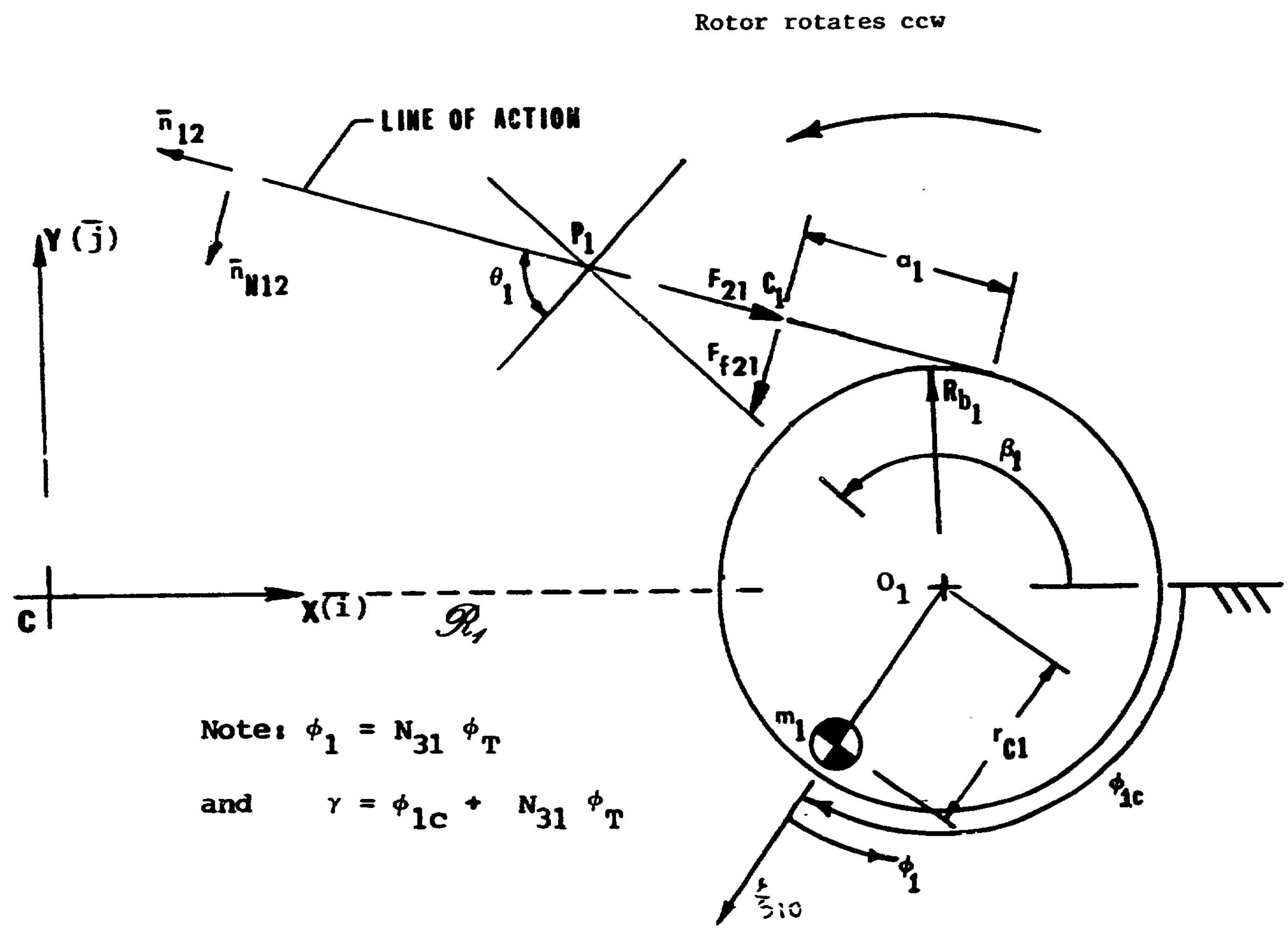
$$- \mu \, F_{x1u} \, \bar{j} + \mu \, F_{y1u} \, \bar{i} + F_{x1L} \, \bar{i} + F_{y1L} \, \bar{j} + \mu \, F_{x1L} \, \bar{j}$$

$$- \mu \, F_{y1L} \, \bar{i} = m_1 \, \bar{A}_{C_1/ground} \qquad \text{(D-307)}$$

According to equation E-127 and E-128 of reference 1

$$\bar{n}_{12} = - \sin(\beta_1 - \theta_1) \, \bar{i} + \cos(\beta_1 - \theta_1) \, \bar{j} \qquad \text{(D-308)}$$

$$\bar{n}_{N12} = -\cos(\beta_1 - \theta_1) \, \bar{i} - \sin(\beta_1 - \theta_1) \, \bar{j} \qquad \text{(D-309)}$$



Note: $\phi_1 = N_{31}\ \phi_T$

and $\gamma = \phi_{1c} + N_{31}\ \phi_T$

Figure D-8a. Top view free body diagram of rotor and gear no. 1

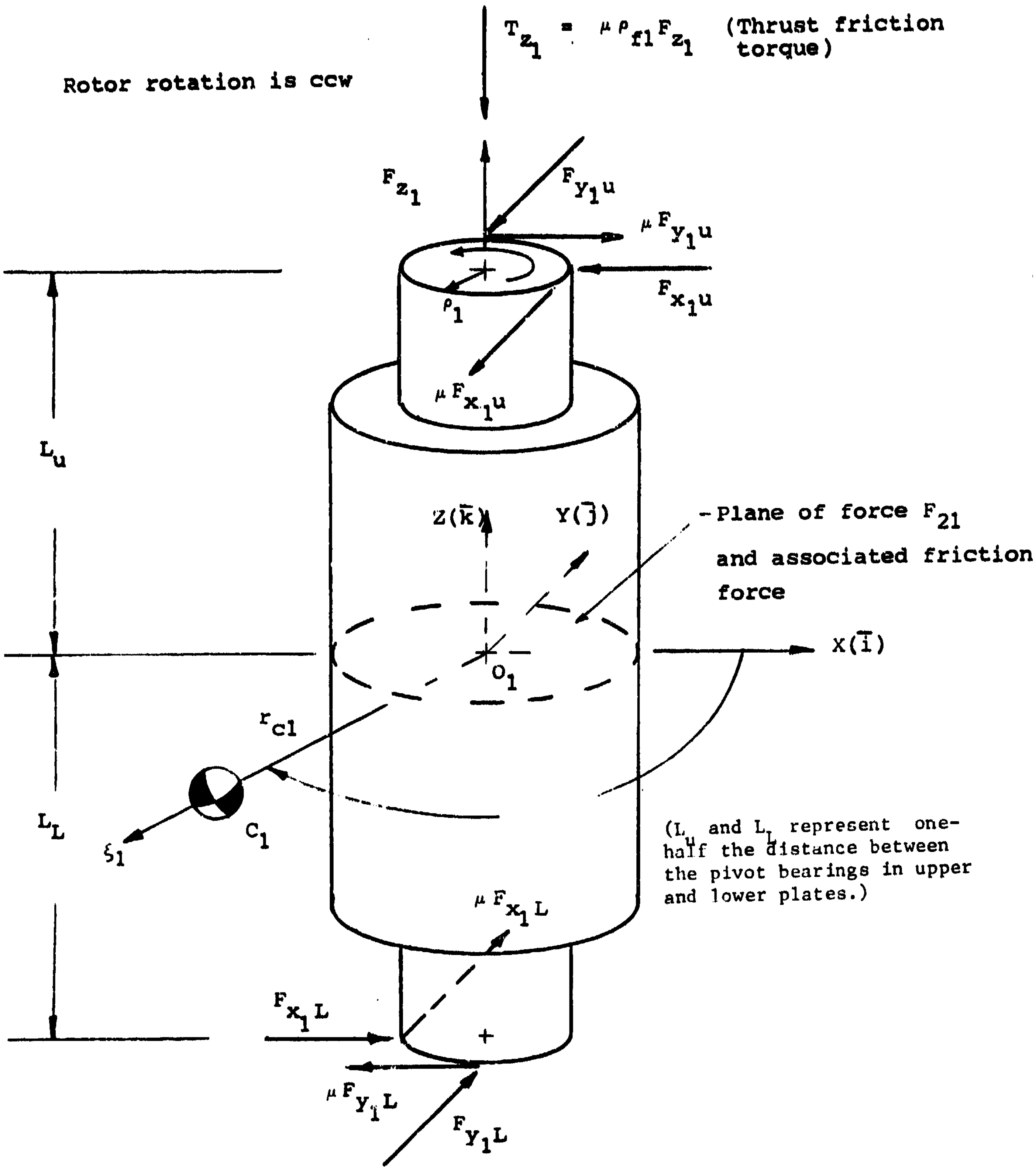


Figure D-8b. Rotor and gear no. 1. Normal forces, friction forces, and thrust friction torque acting on rotor pivots.

The above unit vectors are now substituted into equation D-294. Subsequently, the component expressions of this equation are written with the help of equation D-305:

X-Component of Rotor Force Equation

$$F_{12} \sin(\beta_1 - \theta_1) - \mu s_1 F_{12} \cos(\beta_1 - \theta_1) - F_{x1u} + \mu F_{y1u}$$
$$+ F_{x1L} - \mu F_{y1L} = m_1 [- r_{c1} \{\omega_y^2 \cos\gamma$$
$$- \omega_x \omega_y \sin\gamma + (\omega_z + N_{31} \dot{\phi})^2 \cos\gamma$$
$$+ (\dot{\omega}_z + N_{31} \ddot{\phi}) \sin\gamma \} + O_x] \qquad \text{(D-310)}$$

Y-Component of Rotor Force Equation

$$- F_{12} \cos(\beta_1 - \theta_1) - \mu s_1 F_{12} \sin(\beta_1 - \theta_1) - F_{y1u} - \mu F_{x1u}$$
$$+ F_{y1L} + \mu F_{x1L} = m_1 [- r_{c1} \{\omega_x^2 \sin\gamma$$
$$- \omega_x \omega_y \cos\gamma + (\omega_z + N_{31} \dot{\phi})^2 \sin\gamma$$
$$- (\dot{\omega}_z + N_{31} \ddot{\phi}) \cos\gamma \} + O_y] \qquad \text{(D-311)}$$

Z-Component of Rotor Force Equation

$$F_{z1} = m_1 \{r_{c1} [(\omega_x \cos\gamma + \omega_y \sin\gamma)(\omega_z + 2N_{31} \dot{\phi})$$
$$+ \dot{\omega}_x \sin\gamma - \dot{\omega}_y \cos\gamma] + O_z\} \qquad \text{(D-312)}$$

Factors Entering into Moment Equations for the Rotor

The moment equation for the rotor must be written with respect to the accelerated pivot point O_1. (This is similar to the manner in which the pallet moment expression D-30 was written with respect to point O_p.) Therefore,

$$\bar{M}_{O_1} = - \bar{A}_{O_1/\text{ground}} \times m_1 r_{c1} (\cos\gamma \bar{I} + \sin\gamma \bar{J}) + \dot{\bar{H}}_{O_1} \qquad \text{(D-313)}$$

where

$\bar{M}_{O_1}$ = sum of external moments about point O_1. It is assumed that O_1 lies in the plane of the rotor center of mass, and that F_{12} and $\mu s_1 F_{12}$ also lie in this plane.

$\bar{A}_{O_1/\text{ground}}$ = Absolute acceleration of point O_1 (eq D-291)

$\dot{\bar{H}}_{O_1}$ = Time rate of change of angular momentum of rotor with respect to point O_1. It is obtained by adapting equation B-4 of appendix B to the $\xi_1 - \eta_1 - \zeta_1$ system. The appropriate angular velocity and acceleration components are given by equations A-35 and A-39, respectively. The transformation into the X-Y-Z system is accomplished with the help of the unit vector expressions of equations D-299 to D-301.

Determination of $\bar{M}_{O_1}$

The moments due to the gear contact forces $\bar{F}_{21}$ and $\mu s_1 \bar{F}_{21}$ are identical to those of equation B-129 of reference 1. The moments due to the various bearing forces may be adapted from equation D-32. (Since the rotor always has counterclockwise rotation, let $s_5 = +1$ in equation D-32, change μ_1 to μ, and adjust the subscripts from the primed to the unprimed coordinate system.)

$$\begin{aligned}
\bar{M}_{O_1} = {} & [L_u F_{y1u} + \mu L_u F_{x1u} + L_L F_{y1L} + \mu L_L F_{x1L}] \bar{i} \\
& + [\mu L_u F_{y1u} - L_u F_{x1u} + \mu L_L F_{y1L} - L_L F_{x1L}] \bar{j} \\
& + [- R_{b1} F_{12} + \mu s_1 a_1 F_{12} - \mu \rho_{f1} \tilde{F}_z \\
& - \rho_1 \mu F_{y1u} - \rho_1 \mu F_{x1u} - \rho_1 \mu F_{y1L} - \rho_1 \mu F_{x1L}] \bar{k}
\end{aligned} \tag{D-314}$$

Determination of Right Hand Side of Equation D-313

With the help of equation D-291, the following is obtained for the right hand side of equation D-313

$$- (O_x \bar{i} + O_y \bar{j} + O_z \bar{k}) \times m_1 r_{c1} (\cos \gamma \bar{i} + \sin \gamma \bar{j})$$

$$= m_1 r_{c1} [O_z \sin \gamma \bar{i} - O_z \cos \gamma \bar{j} - (O_x \sin \gamma - O_y \cos \gamma) \bar{k}] \tag{D-315}$$

Determination of Time Rate of Change of Angular Momentum with Respect to Rotor Pivot O_1

To obtain an expression for $\dot{\bar{H}}_{O_1}$ in the $\xi_1 - \eta_1 - \zeta_1$ rotor-fixed system, equation B-4 is first adapted from the X-Y-Z system. Subsequently, the angular velocity and acceleration of equations A-35 and A-39 are substituted as follows:

$$\omega_{\xi_1} = \omega_x \cos\gamma + \omega_y \sin\gamma \tag{D-316}$$

$$\omega_{\eta_1} = -\omega_x \sin\gamma + \omega_y \cos\gamma \tag{D-317}$$

$$\omega_{\zeta_1} = \omega_z + N_{31}\dot{\phi} \tag{D-318}$$

$$\dot{\omega}_{\xi_1} = \dot{\omega}_x \cos\gamma - \omega_x N_{31}\dot{\phi}\sin\gamma + \dot{\omega}_y \sin\gamma + \omega_y N_{31}\dot{\phi}\cos\gamma \tag{D-319}$$

$$\dot{\omega}_{\eta_1} = -\dot{\omega}_x \sin\gamma - \omega_x N_{31}\dot{\phi}\cos\gamma + \dot{\omega}_y \cos\gamma - \omega_y N_{31}\dot{\phi}\sin\gamma \tag{D-320}$$

$$\dot{\omega}_{\zeta_1} = \dot{\omega}_z + N_{31}\ddot{\phi} \tag{D-321}$$

Finally, the body-fixed unit vectors $\bar{n}_{\xi_1}$, $\bar{n}_{\eta_1}$, and $\bar{n}_{\zeta_1}$ are given in the X-Y-Z system according to equations D-299 to D-301. This furnishes

$$\begin{aligned}
\dot{\bar{H}}_{O1} = \{ & I_{\xi\xi_1}(\dot{\omega}_x \cos\gamma - \omega_x N_{31}\dot{\phi}\sin\gamma + \dot{\omega}_y \sin\gamma + \omega_y N_{31}\dot{\phi}\cos\gamma) \\
& + (-\omega_x \sin\gamma + \omega_y \cos\gamma)(\omega_z + N_{31}\dot{\phi})(I_{\zeta\zeta_1} - I_{\eta\eta_1}) \\
& + I_{\xi\eta_1}[(\omega_z + N_{31}\dot{\phi})(\omega_x \cos\gamma + \omega_y \sin\gamma) - (-\dot{\omega}_x \sin\gamma \\
& - \omega_x N_{31}\dot{\phi}\cos\gamma + \dot{\omega}_y \cos\gamma - \omega_y N_{31}\dot{\phi}\sin\gamma)] \\
& - I_{\xi\zeta_1}[(\omega_x \cos\gamma + \omega_y \sin\gamma)(-\omega_x \sin\gamma + \omega_y \cos\gamma) \\
& + (\dot{\omega}_z + N_{31}\ddot{\phi})] - I_{\eta\zeta_1}[(-\omega_x \sin\gamma + \omega_y \cos\gamma)^2 \\
& - (\omega_z + N_{31}\dot{\phi})^2]\}(\cos\gamma\,\bar{i} + \sin\gamma\,\bar{j})
\end{aligned}$$

$$+ \{I_{\eta\eta_1} (- \dot{\omega}_x \sin\gamma - \omega_x N_{31} \dot{\phi} \cos\gamma + \dot{\omega}_y \cos\gamma - \omega_y N_{31} \dot{\phi} \sin\gamma)$$

$$+ (\omega_x \cos\gamma + \omega_y \sin\gamma)(\omega_z + N_{31} \dot{\phi})(I_{\xi\xi_1} - I_{\zeta\zeta_1})$$

$$+ I_{\eta\zeta_1} [(\omega_x \cos\gamma + \omega_y \sin\gamma)(- \omega_x \sin\gamma + \omega_y \cos\gamma) - (\dot{\omega}_z + N_{31} \ddot{\phi})]$$

$$- I_{\xi\eta_1} [(\dot{\omega}_x \cos\gamma - \omega_x N_{31} \dot{\phi} \sin\gamma + \dot{\omega}_y \sin\gamma + \omega_y N_{31} \dot{\phi} \cos\gamma)$$

$$+ (- \omega_x \sin\gamma + \omega_y \cos\gamma)(\omega_z + N_{31} \dot{\phi})] - I_{\xi\zeta_1} [(\omega_z$$

$$+ N_{31} \dot{\phi})^2 - (\omega_x \cos\gamma + \omega_y \sin\gamma)^2]\} (- \sin\gamma \, \bar{i} + \cos\gamma \, \bar{j})$$

$$+ \{I_{\zeta\zeta_1} (\dot{\omega}_z + N_{31} \ddot{\phi}) + (\omega_x \cos\gamma + \omega_y \sin\gamma)(- \omega_x \sin\gamma + \omega_y \cos\gamma)$$

$$\times (I_{\eta\eta_1} - I_{\xi\xi_1}) + I_{\zeta\xi_1} [(- \omega_x \sin\gamma + \omega_y \cos\gamma)(\omega_z + N_{31} \dot{\phi})$$

$$- (\dot{\omega}_x \cos\gamma - \omega_x N_{31} \dot{\phi} \sin\gamma + \dot{\omega}_y \sin\gamma + \omega_y N_{31} \dot{\phi} \cos\gamma)]$$

$$- I_{\zeta\eta_1} [(- \dot{\omega}_x \sin\gamma - \omega_x N_{31} \dot{\phi} \cos\gamma + \dot{\omega}_y \cos\gamma - \omega_y N_{31} \dot{\phi} \sin\gamma)$$

$$+ (\omega_x \cos\gamma + \omega_y \sin\gamma)(\omega_z + N_{31} \dot{\phi})] - I_{\xi\eta_1} [(\omega_x \cos\gamma$$

$$+ \omega_y \sin\gamma)^2 - (- \omega_x \sin\gamma + \omega_y \cos\gamma)^2]\} \bar{k} \qquad \text{(D-322)}$$

The components $\dot{H}_{O_{1x}}$, $\dot{H}_{O_{1y}}$, and $\dot{H}_{O_{1z}}$ must now be determined from equation D-322. This leads to:

$$\dot{H}_{O_{1x}} = A_{52} + A_{53} \dot{\phi} + A_{54} \dot{\phi}^2 + A_{55} \ddot{\phi}$$

where

$$A_{52} = \cos\gamma\,\{I_{\xi\xi_1}\,(\dot{\omega}_x \cos\gamma + \dot{\omega}_y \sin\gamma)$$

$$+ (I_{\zeta\zeta_1} - I_{\eta\eta_1})\,\omega_z\,(-\,\omega_x \sin\gamma + \omega_y \cos\gamma)$$

$$+ I_{\xi\eta_1}\,[\omega_z\,(\omega_x \cos\gamma + \omega_y \sin\gamma) + (\dot{\omega}_x \sin\gamma - \dot{\omega}_y \cos\gamma)]$$

$$- I_{\xi\zeta_1}\,[(\omega_x \cos\gamma + \omega_y \sin\gamma)(-\,\omega_x \sin\gamma + \omega_y \cos\gamma) + \dot{\omega}_z]$$

$$- I_{\eta\zeta_1}\,[(-\,\omega_x \sin\gamma + \omega_y \cos\gamma)^2 - \omega_z^{\,2}]\}$$

$$- \sin\gamma\,\{I_{\eta\eta_1}\,(-\,\dot{\omega}_x \sin\gamma + \dot{\omega}_y \cos\gamma)$$

$$+ (I_{\xi\xi_1} - I_{\zeta\zeta_1})\,\omega_z\,(\omega_x \cos\gamma + \omega_y \sin\gamma)$$

$$+ I_{\eta\zeta_1}\,[(\omega_x \cos\gamma + \omega_y \sin\gamma)(-\,\omega_x \sin\gamma + \omega_y \cos\gamma) - \dot{\omega}_z]$$

$$- I_{\xi\eta_1}\,[(\dot{\omega}_x \cos\gamma + \dot{\omega}_y \sin\gamma) + \omega_z\,(-\,\omega_x \sin\gamma + \omega_y \cos\gamma)]$$

$$- I_{\xi\zeta_1}\,[\omega_z^{\,2} - (\omega_x \cos\gamma + \omega_y \sin\gamma)^2]\} \qquad \text{(D-324)}$$

$$A_{53} = N_{31}\,\{[-\,\omega_x \sin\gamma + \omega_y \cos\gamma]\,[(I_{\xi\xi_1} + I_{\zeta\zeta_1} - I_{\eta\eta_1}) \cos\gamma$$

$$+ 2I_{\xi\eta_1} \sin\gamma] + [\omega_x \cos\gamma + \omega_y \sin\gamma][(I_{\eta\eta_1} - I_{\xi\xi_1} + I_{\zeta\zeta_1}) \sin\gamma$$

$$+ 2I_{\xi\eta_1} \cos\gamma] + 2\,\omega_z\,[I_{\eta\xi_1} \cos\gamma + I_{\xi\zeta_1} \sin\gamma] \qquad \text{(D-325)}$$

$$A_{54} = N_{31}^2\,[I_{\eta\xi_1} \cos\gamma + I_{\xi\zeta_1} \sin\gamma] \qquad \text{(D-326)}$$

$$A_{55} = N_{31}\,[-\,I_{\xi\zeta_1} \cos\gamma + I_{\eta\zeta_1} \sin\gamma] \qquad \text{(D-327)}$$

Further,

$$\dot{H}_{O_{1y}} = A_{56} + A_{57}\,\dot{\phi} + A_{58}\,\dot{\phi}^2 + A_{59}\,\ddot{\phi} \tag{D-328}$$

$$\begin{aligned}
A_{56} = \sin\gamma\,\{&I_{\xi\xi_1}\,(\dot{\omega}_x\cos\gamma + \dot{\omega}_y\sin\gamma) \\
&+ (I_{\zeta\zeta_1} - I_{\eta\eta_1})(-\,\omega_x\sin\gamma + \omega_y\cos\gamma)\,\omega_z \\
&+ I_{\xi\eta_1}\,[\omega_z\,(\omega_x\cos\gamma + \omega_y\sin\gamma) - (-\,\dot{\omega}_x\sin\gamma + \dot{\omega}_y\cos\gamma)] \\
&- I_{\xi\zeta_1}\,[(\omega_x\cos\gamma + \omega_y\sin\gamma)(-\,\omega_x\sin\gamma + \omega_y\cos\gamma) + \dot{\omega}_z] \\
&- I_{\eta\zeta_1}\,[(-\,\omega_x\sin\gamma + \omega_y\cos\gamma)^2 - \omega_z^{\,2}]\} \\
+ \cos\gamma\,\{&I_{\eta\eta_1}\,(-\,\dot{\omega}_x\sin\gamma + \dot{\omega}_y\cos\gamma) \\
&+ (I_{\xi\xi_1} - I_{\zeta\zeta_1})(\omega_x\cos\gamma + \omega_y\sin\gamma)\,\omega_z \\
&+ I_{\eta\zeta_1}\,[(\omega_x\cos\gamma + \omega_y\sin\gamma)(-\,\omega_x\sin\gamma + \omega_y\cos\gamma) - \dot{\omega}_z] \\
&- I_{\xi\eta_1}\,[\dot{\omega}_x\cos\gamma + \dot{\omega}_y\sin\gamma + \omega_z\,(-\,\omega_x\sin\gamma + \omega_y\cos\gamma)] \\
&- I_{\xi\zeta_1}\,[\omega_z^{\,2} - (\omega_x\cos\gamma + \omega_y\sin\gamma)^2]\}
\end{aligned} \tag{D-329}$$

$$\begin{aligned}
A_{57} = N_{31}\,\{&[-\,\omega_x\sin\gamma + \omega_y\cos\gamma] \\
&\times [(I_{\xi\xi_1} + I_{\zeta\zeta_1} - I_{\eta\eta_1})\sin\gamma - 2\,I_{\xi\eta_1}\cos\gamma] \\
&+ [\omega_x\cos\gamma + \omega_y\sin\gamma] \\
&\times [2\,I_{\xi\eta_1}\sin\gamma + (I_{\xi\xi_1} - I_{\zeta\zeta_1} - I_{\eta\eta_1})\cos\gamma] \\
&+ 2\,\omega_z\,[I_{\eta\zeta_1}\sin\gamma - I_{\xi\zeta_1}\cos\gamma]\}
\end{aligned} \tag{D-330}$$

$$A_{58} = N_{31}^2 \left[I_{\eta\zeta_1} \sin\gamma - I_{\xi\zeta_1} \cos\gamma\right] \tag{D-331}$$

$$A_{59} = - N_{31} \left[I_{\xi\zeta_1} \sin\gamma + I_{\eta\zeta_1} \cos\gamma\right] \tag{D-332}$$

Finally,

$$\dot{H}_{0_{1z}} = A_{60} + A_{61} \ddot{\phi} \tag{D-333}$$

where

$$\begin{aligned} A_{60} = {} & I_{\zeta\zeta_1} \dot{\omega}_z + (I_{\eta\eta_1} - I_{\xi\xi_1})(\omega_x \cos\gamma + \omega_y \sin\gamma) \\ & \times (- \omega_x \sin\gamma + \omega_y \cos\gamma) \\ & + I_{\zeta\xi_1} \left[(- \omega_x \sin\gamma + \omega_y \cos\gamma)\, \omega_z - \dot{\omega}_x \cos\gamma - \dot{\omega}_y \sin\gamma\right] \\ & + I_{\zeta\eta_1} \left[\dot{\omega}_x \sin\gamma - \dot{\omega}_y \cos\gamma - \omega_z (\omega_x \cos\gamma + \omega_y \sin\gamma)\right] \\ & - I_{\xi\eta_1} \left[(\omega_x \cos\gamma + \omega_y \sin\gamma)^2 - (- \omega_x \sin\gamma + \omega_y \cos\gamma)^2\right] \end{aligned} \tag{D-334}$$

$$A_{61} = N_{31} I_{\zeta\zeta_1} \tag{D-335}$$

Simplification of Force Equations for the Rotor

X-Component of the Force Equation

Equation D-310 is now rewritten in the following manner:

$$\begin{aligned} & - F_{x1u} + \mu F_{y1u} + F_{x1L} - \mu F_{y1L} \\ & = A_{62} + A_{63} \dot{\phi} + A_{64} \dot{\phi}^2 + A_{65} \ddot{\phi} + A_{66} F_{12} \end{aligned} \tag{D-336}$$

where

$$A_{62} = m_1\, r_{c1}\, [-\, \omega_y^{\,2} \cos\, \gamma + \omega_x\, \omega_y \sin\, \gamma$$
$$-\, \omega_z^{\,2} \cos\, \gamma - \dot{\omega}_z \sin\, \gamma] + m_1\, O_x \tag{D-337}$$

$$A_{63} = -\, 2\, m_1\, r_{c1}\, \omega_z\, N_{31} \cos\, \gamma \tag{D-338}$$

$$A_{64} = -\, m_1\, r_{c1}\, N_{31}^2 \cos\, \gamma \tag{D-339}$$

$$A_{65} = -\, m_1\, r_{c1}\, N_{31} \sin\, \gamma \tag{D-340}$$

$$A_{66} = \mu\, s_1 \cos\, (\beta_1 - \theta_1) - \sin\, (\beta_1 - \theta_1) \tag{D-341}$$

Y-Component of the Force Equation

Equation D-311 becomes:

$$-\, F_{y1u} - \mu\, F_{x1u} + F_{y1L} + \mu\, F_{x1L}$$
$$= A_{67} + A_{68}\, \dot{\phi} + A_{69}\, \dot{\phi}^2 + A_{70}\, \ddot{\phi} + A_{71}\, F_{12} \tag{D-342}$$

where

$$A_{67} = m_1\, r_{c1}\, [-\, \omega_x^{\,2} \sin\, \gamma + \omega_x\, \omega_y \cos\, \gamma$$
$$-\, \omega_z^{\,2} \sin\, \gamma + \dot{\omega}_z \cos\, \gamma] + m_1\, O_y \tag{D-343}$$

$$A_{68} = -\, 2\, m_1\, r_{c1}\, N_{31}\, \omega_z \sin\, \gamma \tag{D-344}$$

$$A_{69} = -\, m_1\, r_{c1}\, N_{31}^2 \sin\, \gamma \tag{D-345}$$

$$A_{70} = -\, m_1\, r_{c1}\, N_{31} \cos\, \gamma \tag{D-346}$$

$$A_{71} = \cos\, (\beta_1 - \theta_1) + \mu\, s_1 \sin\, (\beta_1 - \theta_1) \tag{D-347}$$

Z-Component of Force Equation

Equation D-312 is rewritten in its tilded form directly:

$$\tilde{F}_{z1} = A_{72} + A_{73}\,\dot{\phi} \tag{D-348}$$

where

$$A_{72} = |m_1\, r_{c1}\, [\omega_z\, (\omega_x \cos\gamma + \omega_y \sin\gamma) + \dot{\omega}_x \sin\gamma - \dot{\omega}_y \cos\gamma] + m_1\, O_z| \tag{D-349}$$

$$A_{73} = |2\, m_1\, r_{c1}\, N_{31}\, [\omega_x \cos\gamma + \omega_y \sin\gamma]| \tag{D-350}$$

Simplification of Moment Equations for the Rotor

The components of the rotor moment equations are now written according to equation D-313.

X-Component of Moment Equation

With the help of equations D-314, D-315, and D-323, the following is obtained:

$$\mu L_u F_{xlu} + L_u F_{ylu} + \mu L_L F_{xlL} + L_L F_{ylL} = m_1\, r_{c1}\, O_z \sin\gamma + A_{52} + A_{53}\,\dot{\phi} + A_{54}\,\dot{\phi}^2 + A_{55}\,\ddot{\phi} \tag{D-351}$$

Y-Component of Moment Equation

Again with the help of equations D-314 and D-315, i.e., its y-factors, as well as equation D-328, the following is found:

$$-L_u F_{xlu} + \mu L_u F_{ylu} + \mu L_L F_{ylL} - L_L F_{xlL} = -\, m_1\, r_{c1}\, O_z \cos\gamma + A_{56} + A_{57}\,\dot{\phi} + A_{58}\,\dot{\phi}^2 + A_{59}\,\ddot{\phi} \tag{D-352}$$

Z-Component of Moment Equation

Again, using the Z-components of equations D-314 and D-315, together with equation D-333, obtained for the Z-component of the moment expression

$$- R_{b1} F_{12} + \mu s_1 a_1 F_{12} - \mu \rho_{\varepsilon 1} \tilde{F}_z - \mu \rho_1 (F_{x1u} + F_{y1u} + F_{x1L} + F_{y1L})$$

$$= - m_1 r_{c1} [O_x \sin \gamma - O_y \cos \gamma] + A_{60} + A_{61} \ddot{\phi} \qquad \text{(D-353)}$$

Solution of Rotor Pivot Forces

To obtain the rotor pivot forces, equations D-336, D-342, D-351, and D-352 must be solved simultaneously. Therefore,

$$- F_{x1u} + \mu F_{y1u} + F_{x1L} - \mu F_{y1L} = B_{11} \qquad \text{(D-354)}$$

$$- \mu F_{x1u} - F_{y1u} + \mu F_{x1L} + F_{y1L} = B_{12} \qquad \text{(D-355)}$$

$$\mu L_u F_{x1u} + L_u F_{y1u} + \mu L_L F_{x1L} + L_L F_{y1L} = B_{13} \qquad \text{(D-356)}$$

$$- L_u F_{x1u} + \mu L_u F_{y1u} - L_L F_{x1L} + \mu L_L F_{y1L} = B_{14} \qquad \text{(D-357)}$$

where

$$B_{11} = A_{62} + A_{63} \dot{\phi} + A_{64} \dot{\phi}^2 + A_{65} \ddot{\phi} + A_{66} F_{12} \qquad \text{(D-358)}$$

$$B_{12} = A_{67} + A_{68} \dot{\phi} + A_{69} \dot{\phi}^2 + A_{70} \ddot{\phi} + A_{71} F_{12} \qquad \text{(D-359)}$$

$$B_{13} = m_1 r_{c1} O_z \sin \gamma + A_{52} + A_{53} \dot{\phi} + A_{54} \dot{\phi}^2 + A_{55} \ddot{\phi} \qquad \text{(D-360)}$$

$$B_{14} = - m_1 r_{c1} O_z \cos \gamma + A_{56} + A_{57} \dot{\phi} + A_{58} \dot{\phi}^2 + A_{59} \ddot{\phi} \qquad \text{(D-361)}$$

Since equations D-354 to D-357 together have the same general form as equation D-67 for the pallet, the forms of the pallet pivot force solutions for the rotor pivot forces may be used. It must be kept in mind that for the rotor the factor μ must be substituted for A_{11}. Then, according to equation D-73:

$$D_1 = [(L_u + L_L)(1 + \mu^2)]^2 \qquad \text{(D-362)}$$

Parallel to equation D-80, the determinant $D_{F_{x1u}}$ becomes:

$$D_{F_{x1u}} = (L_u + L_L)(1 + \mu^2)[- L_L B_{11} - \mu L_L B_{12} + \mu B_{13} - B_{14}] \qquad \text{(D-363)}$$

After appropriate substitution of equations D-358 to D-361, parallel to equations D-81 to D-87, the following is obtained for the conservative rotor pivot force:

$$\tilde{F}_{x1u} = \frac{\tilde{D}_{F_{x1u}}}{D_1} = \frac{1}{L_T\ (1+\mu^2)}\left[C_{37} + C_{38}\ \dot{\phi} + C_{39}\ \dot{\phi}^2 + C_{40}\ \ddot{\phi} + C_{41}\ F_{12}\right] \tag{D-364}$$

where

$$C_{37} = \left|-L_L\ A_{62} + \mu\ (A_{52} - L_L\ A_{67}) - A_{56} + m_1\ r_{c1}\ O_z\ [\mu \sin\gamma + \cos\gamma]\right| \tag{D-365}$$

$$C_{38} = \left|-L_L\ A_{63} + \mu\ (A_{53} - L_L\ A_{68}) - A_{57}\right| \tag{D-366}$$

$$C_{39} = \left|-L_L\ A_{64} + \mu\ (A_{54} - L_L\ A_{69}) - A_{58}\right| \tag{D-367}$$

$$C_{40} = \left|-L_L\ A_{65} + \mu\ (A_{55} - L_L\ A_{70}) - A_{59}\right| \tag{D-368}$$

$$C_{41} = \left|-L_L\ (A_{66} + \mu\ A_{71})\right| \tag{D-369}$$

Parallel to equation D-89, the determinant $D_{F_{y1u}}$ becomes:

$$D_{F_{y1u}} = (L_u + L_L)(1+\mu^2)\ \{\mu\ L_L\ B_{11} - L_L\ B_{12} + B_{13} + \mu\ B_{14}\} \tag{D-370}$$

After appropriate substitution of equations D-358 to D-361, parallel to equations D-91 to D-96, it is found that:

$$\tilde{F}_{y1u} = \frac{\tilde{D}_{F_{y1u}}}{D_1} = \frac{1}{L_T\ (1+\mu^2)}\left[C_{42} + C_{43}\ \dot{\phi} + C_{44}\ \dot{\phi}^2 + C_{45}\ \ddot{\phi} + C_{46}\ F_{12}\right] \tag{D-371}$$

where

$$C_{42} = \left|-L_L\ A_{67} + \mu\ (A_{56} + L_L\ A_{62}) + A_{52} + m_1\ r_{c1}\ O_z\ [\sin\gamma - \mu\cos\gamma]\right| \tag{D-372}$$

$$C_{43} = |- L_L A_{68} + \mu (L_L A_{63} + A_{57}) + A_{53}| \qquad \text{(D-373)}$$

$$C_{44} = |- L_L A_{69} + \mu (L_L A_{64} + A_{58}) + A_{54}| \qquad \text{(D-374)}$$

$$C_{45} = |- L_L A_{70} + \mu (L_L A_{65} + A_{59}) + A_{55}| \qquad \text{(D-375)}$$

$$C_{46} = |L_L (\mu A_{66} - A_{71})| \qquad \text{(D-376)}$$

Parallel to equation D-99, the determinant $D_{F_{x1L}}$ becomes:

$$D_{F_{x1L}} = (L_u + L_L)(1 + \mu^2) \{L_u B_{11} + \mu L_u B_{12} + \mu B_{13} - B_{14}\} \qquad \text{(D-377)}$$

Again, equations D-358 to D-361 are substituted into the above. Then proceed parallel to equations D-101 to D-106. Finally,

$$\tilde{F}_{x1L} = \frac{\tilde{D}_{F_{x1L}}}{D_1} = \frac{1}{L_T (1 + \mu^2)} [C_{47} + C_{48} \dot{\phi} + C_{49} \dot{\phi}^2 + C_{50} \ddot{\phi} + C_{51} F_{12}] \qquad \text{(D-378)}$$

$$C_{47} = |L_u A_{62} + \mu (L_u A_{67} + A_{52}) - A_{56} + m_1 r_{c1} O_z [\mu \sin \gamma + \cos \gamma]| \qquad \text{(D-379)}$$

$$C_{48} = |L_u A_{63} + \mu (L_u A_{68} + A_{53}) - A_{57}| \qquad \text{(D-380)}$$

$$C_{49} = |L_u A_{64} + \mu (L_u A_{69} + A_{54}) - A_{58}| \qquad \text{(D-381)}$$

$$C_{50} = |L_u A_{65} + \mu (L_u A_{70} + A_{55}) - A_{59}| \qquad \text{(D-382)}$$

$$C_{51} = |L_u (A_{66} + \mu A_{71})| \qquad \text{(D-383)}$$

Parallel to equation D-109, the determinant $D_{F_{y1L}}$ becomes:

$$D_{F_{y1L}} = (L_u + L_L)(1 + \mu^2) \{- \mu L_u B_{11} + L_u B_{12} + B_{13} + \mu B_{14}\} \qquad \text{(D-384)}$$

After substitution of equations D-358 to D-361, proceed parallel to equation D-111:

$$\tilde{F}_{y1L} = \frac{\tilde{D}_{F_{y1L}}}{D_1} = \frac{1}{L_T\left(1 + \mu^2\right)}\left[C_{52} + C_{53}\,\dot{\phi} + C_{54}\,\dot{\phi}^2 + C_{55}\,\ddot{\phi} + C_{56}\,F_{12}\right] \qquad \text{(D-385)}$$

where

$$C_{52} = \left|L_u\,A_{67} + \mu\left(A_{56} - L_u\,A_{62}\right) + A_{52} + m_1\,r_{c1}\,O_z\left[\sin\gamma - \mu\cos\gamma\right]\right| \qquad \text{(D-386)}$$

$$C_{53} = \left|L_u\,A_{68} + \mu\left(A_{57} - L_u\,A_{63}\right) + A_{53}\right| \qquad \text{(D-387)}$$

$$C_{54} = \left|L_u\,A_{69} + \mu\left(A_{58} - L_u\,A_{64}\right) + A_{54}\right| \qquad \text{(D-388)}$$

$$C_{55} = \left|L_u\,A_{70} + \mu\left(A_{59} - L_u\,A_{65}\right) + A_{55}\right| \qquad \text{(D-389)}$$

$$C_{56} = \left|L_u\left(A_{71} - \mu\,A_{66}\right)\right| \qquad \text{(D-390)}$$

Substitution of Tilded Pivot Forces Into Z-Component of Moment Equation

The sum of the pivot forces in equation D-353 is replaced by the sum of the tilded pivot forces, as given by equations D-364, D-371, D-378, and D-385. Then

$$F_{x1u} + F_{y1u} + F_{x1L} + F_{y1L} \approx \tilde{F}_{x1u} + \tilde{F}_{y1u} + \tilde{F}_{x1L} + \tilde{F}_{y1L}$$

$$= A_{74} + A_{75}\,\dot{\phi} + A_{76}\,\dot{\phi}^2 + A_{77}\,\ddot{\phi} + A_{78}\,F_{12} \qquad \text{(D-391)}$$

where

$$A_{74} = \frac{C_{37} + C_{42} + C_{47} + C_{52}}{L_T\left(1 + \mu^2\right)} \qquad \text{(D-392)}$$

$$A_{75} = \frac{C_{38} + C_{43} + C_{48} + C_{53}}{L_T\left(1 + \mu^2\right)} \qquad \text{(D-393)}$$

$$A_{76} = \frac{C_{39} + C_{44} + C_{49} + C_{54}}{L_T\left(1 + \mu^2\right)} \qquad \text{(D-394)}$$

$$A_{77} = \frac{C_{40} + C_{45} + C_{50} + C_{55}}{L_T \left(1 + \mu^2\right)} \qquad \text{(D-395)}$$

$$A_{78} = \frac{C_{41} + C_{46} + C_{51} + C_{56}}{L_T \left(1 + \mu^2\right)} \qquad \text{(D-396)}$$

The above is now substituted, together with the thrust friction according to equation D-348, into the moment expression D-353:

$$- R_{b1}\, F_{12} + \mu\, s_1\, a_1\, F_{12} - \mu\, \rho_{f1} \left[A_{72} + A_{73}\, \dot{\phi}\right]$$

$$- \mu\, \rho_1 \left[A_{74} + A_{75}\, \dot{\phi} + A_{76}\, \dot{\phi}^2 + A_{77}\, \ddot{\phi} + A_{78}\, F_{12}\right]$$

$$= - m_1\, r_{c1} \left[O_x \sin \gamma - O_y \cos \gamma\right] + A_{60} + A_{61}\, \ddot{\phi} \qquad \text{(D-397)}$$

The above is rearranged to:

$$- F_{12} \left[R_{b1} - \mu\, s_1\, a_1 + \mu\, \rho_1\, A_{78}\right] + \mu \left[\rho_{f1}\, A_{72} + \rho_1\, A_{74}\right]$$

$$+ \mu \left[\rho_{f1}\, A_{73} + \rho_1\, A_{75}\right] \dot{\phi} + \mu\, \rho_1\, A_{76}\, \dot{\phi}^2 + \mu\, \rho_1\, A_{77}\, \ddot{\phi}$$

$$= A_{60} + A_{61}\, \ddot{\phi} - m_1\, r_{c1} \left[O_x \sin \gamma - O_y \cos \gamma\right] \qquad \text{(D-398)}$$

Now consider the signs of the various friction moments, recalling that a reversal in the gear train motion will cause a change in the sign of μ in the program. The following moment components must have negative signs during positive rotation (note also that N_{31} is positive):

$$1: \quad - \mu\, F_{12}\, \rho_1\, A_{78} \qquad \text{(D-399)}$$

since F_{12} and ρ_1 are positive, and A_{78} is a sum of absolute values.

$$2: \quad - \mu \left[\rho_{f1}\, A_{72} + \rho_1\, A_{74}\right] \qquad \text{(D-400)}$$

since ρ_{f1} and ρ_1 are positive, while A_{72} and A_{74} are both absolute values.

$$3: \quad -\mu \rho_1 A_{76} \dot{\phi}^2 \qquad \text{(D-401)}$$

since A_{76} is also a sum of absolute values.

The sign of the term containing $\dot{\phi}$ must be decided by the sign of this angular velocity only. Therefore, the coefficient of friction must not change sign on motion reversal, and the expression takes the form:

$$-|\mu| \left[\rho_{f1} A_{73} + \rho_1 A_{75}\right] \dot{\phi} \qquad \text{(D-402)}$$

The choice of signs in the coefficient of the angular acceleration $\ddot{\phi}$ is discussed in detail in appendix F of reference 2. This leads to the computational rules of equations D-409 and D-410 below.

With the above considerations, equation D-398 becomes:

$$- A_{79} F_{12} - A_{80} - A_{81} \dot{\phi} - A_{82} \dot{\phi}^2$$

$$= I_{1R} \ddot{\phi} + A_{60} - m_1 r_{c1} \left[O_x \sin \gamma - O_y \cos \gamma\right] \qquad \text{(D-403)}$$

where

$$A_{79} = R_{b1} - \mu s_1 a_1 + \mu \rho_1 A_{78} \qquad \text{(D-404)}$$

$$A_{80} = \mu \left[\rho_{f1} A_{72} + \rho_1 A_{74}\right] \qquad \text{(D-405)}$$

$$A_{81} = |\mu| \left[\rho_{f1} A_{73} + \rho_1 A_{75}\right] \qquad \text{(D-406)}$$

$$A_{82} = \mu \rho_1 A_{76} \qquad \text{(D-407)}$$

$$A_{83} = |\mu| \rho_1 A_{77} \qquad \text{(D-408)}$$

Further

$$I_{1R} = A_{61} + A_{83} \qquad \text{(D-409)}$$

when $\dot{\phi}$ and $\ddot{\phi}$ have the same signs, and

$$I_{1R} = A_{61} - A_{83} \qquad \text{(D-410)}$$

Expression for Contact Force F_{12}

Equation D-403 may be rewritten to obtain an expression for the contact force F_{12}:

$$F_{12} = \frac{- I_{1R}\ \ddot{\phi} - A_{81}\ \dot{\phi} - A_{82}\ \dot{\phi}^2 - A_{80} - A_{60} + m_1\ r_{c1}\left[O_x \sin\gamma - O_y \cos\gamma\right]}{A_{79}} \tag{D-411}$$

Dynamics of Gear and Pinion No. 2

Before the force and moment equations for gear and pinion no. 2 can be written, it is first necessary to find an expression for the absolute acceleration of the gear and pinion pivot point O_2, which coincides with the center of mass C_2 of this component. A top view of gear and pinion no. 2 in the mechanism plane is shown in figure D-9.

Absolute Acceleration of Gear and Pinion Pivot O_2

The absolute acceleration of pivot point O_2 is given by:

$$\bar{A}_{O_2/\text{ground}} = \bar{A}_{O_2/C} + \bar{A}_{C/\text{ground}} \tag{D-412}$$

where

$A_{C/\text{ground}}$ = Absolute acceleration of geometric center C of mechanism plane, as given by equation C-4.

and

$$\bar{A}_{O_2/C} = \bar{\omega} \times \left(\omega \times \mathcal{R}_2\ \bar{n}_2\right) + \dot{\bar{\omega}} \times \mathcal{R}_2\ \bar{n}_2 \tag{D-413}$$

where

$$\bar{\omega} = \omega_x\ \bar{i} + \omega_y\ \bar{j} + \omega_z\ \bar{k} \tag{D-414}$$

$$\dot{\bar{\omega}} = \dot{\omega}_x\ \bar{i} + \dot{\omega}_y\ \bar{j} + \dot{\omega}_z\ \bar{k} \tag{D-415}$$

Further

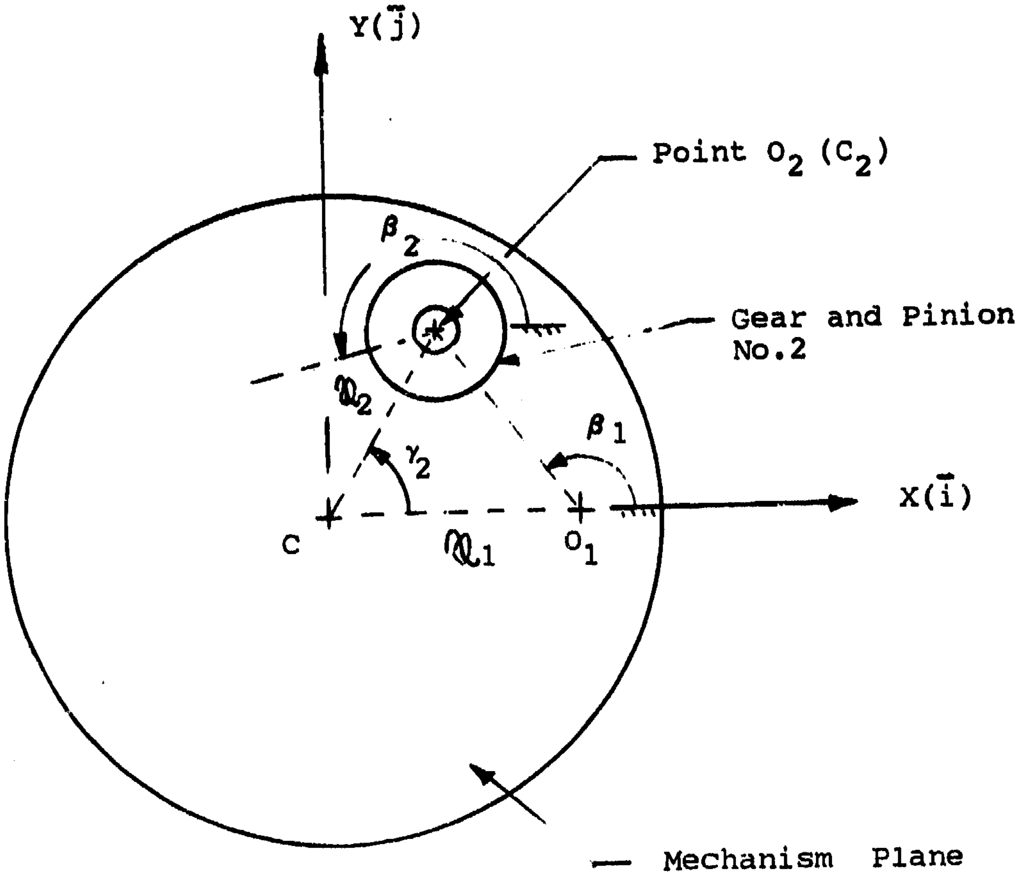


Figure D-9. Top view of gear and pinion no. 2 in mechanism plane

$$\bar{n}_2 = \cos \gamma_2 \; \bar{i} + \sin \gamma_2 \; \bar{j} \tag{D-416}$$

and

$$\mathcal{R}_{2x} = \mathcal{R}_2 \cos \gamma_2 \tag{D-417}$$

$$\mathcal{R}_{2y} = \mathcal{R}_2 \sin \gamma_2 \tag{D-418}$$

With the above, equation D-413 becomes:

$$\bar{A}_{O_2/C} = P_x \; \bar{i} + P_y \; \bar{j} + P_z \; \bar{k} \tag{D-419}$$

where

$$P_x = \omega_x \, \omega_y \, \mathcal{R}_{2y} - (\omega_y^{\,2} + \omega_z^{\,2}) \, \mathcal{R}_{2x} - \dot{\omega}_z \, \mathcal{R}_{2y} \tag{D-420}$$

$$P_y = \omega_x \, \omega_y \, \mathcal{R}_{2x} - (\omega_x^{\,2} + \omega_z^{\,2}) \, \mathcal{R}_{2y} + \dot{\omega}_z \, \mathcal{R}_{2x} \tag{D-421}$$

$$P_z = (\omega_x \, \mathcal{R}_{2x} + \omega_y \, \mathcal{R}_{2y}) \, \omega_z + \dot{\omega}_x \, \mathcal{R}_{2y} - \dot{\omega}_y \, \mathcal{R}_{2x} \tag{D-422}$$

Finally, equation D-412 becomes:

$$\bar{A}_{O_2/\text{ground}} = Q_x \; \bar{i} + Q_y \; \bar{j} + Q_z \; \bar{k} \tag{D-423}$$

where, with the help of equations C-4 and D-419:

$$Q_x = G_x + P_x \tag{D-424}$$

$$Q_y = G_y + P_y \tag{D-425}$$

$$Q_z = G_z + P_z \tag{D-426}$$

Force Equations for Gear and Pinion No. 2

A top view of gear and pinion no. 2, showing the contact forces F_{32} and F_{12} together with their associated friction forces is given in figure D-10a. A free-body diagram of the pivot shaft of this component is shown in figure D-10b.

The force equation is again based on Newton's law, i.e.:

Gear and pinion 2 rotates cw

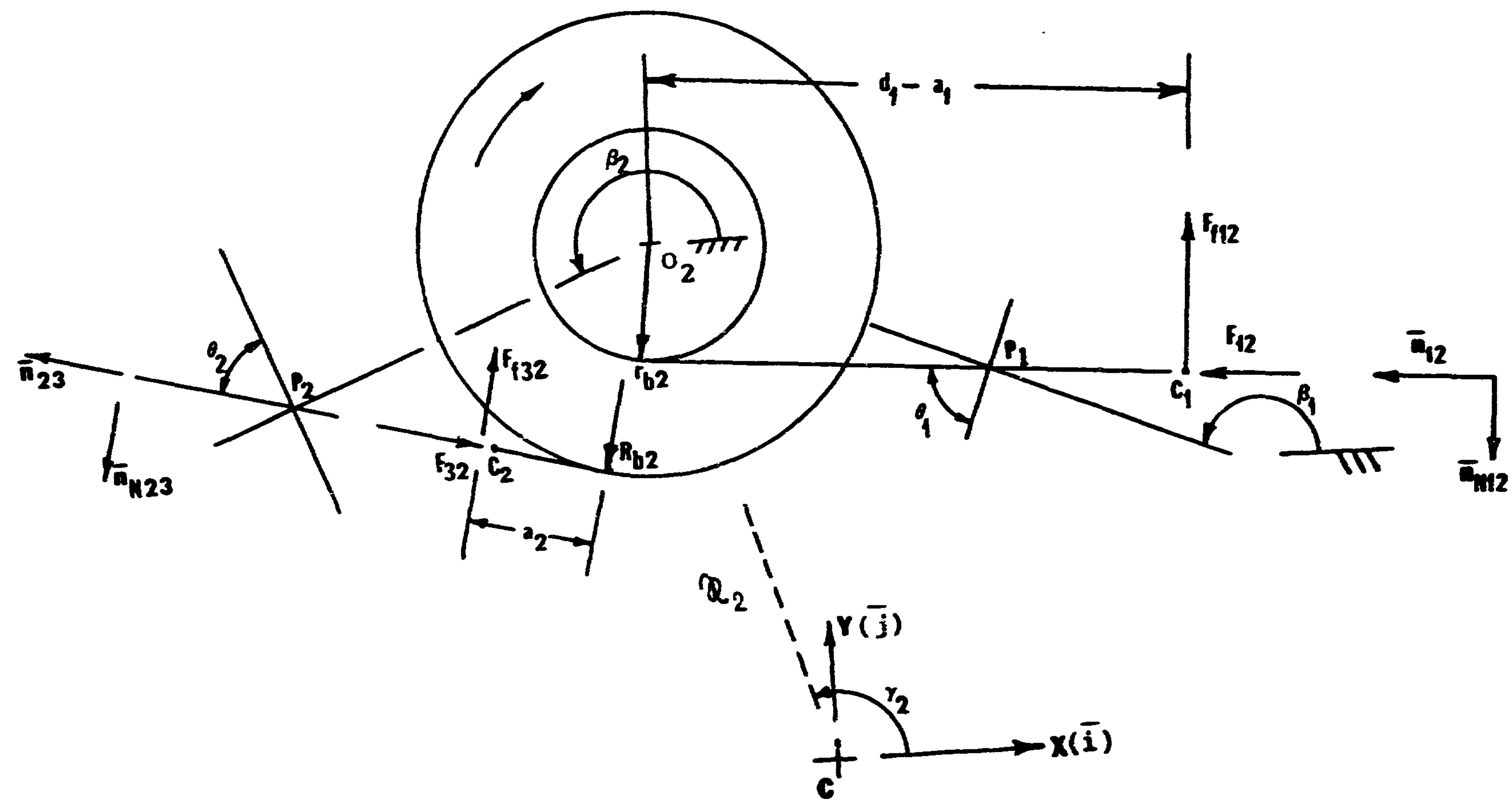


Figure D-10a. Top view free body diagram of gear and pinion no. 2

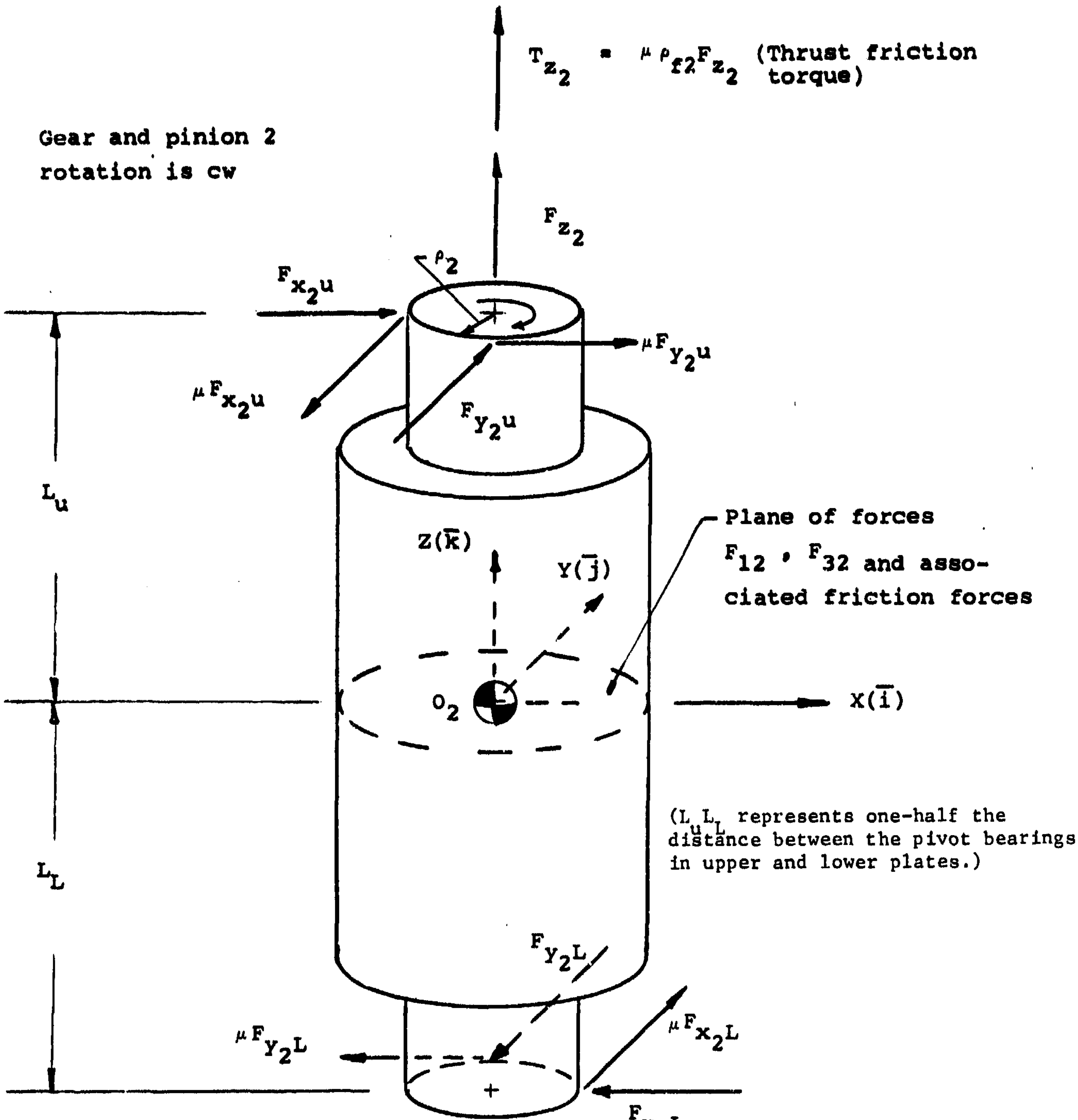


Figure D-10b. Gear and pinion no. 2. Normal forces, friction forces, and thrust friction torque on pivots.

The force equation is again based on Newton's law, i.e.:

$$\Sigma \bar{F} = m_2 \bar{A}_{0_2/ground} \tag{D-427}$$

where

$\Sigma \bar{F}$ = Sum of the pivot forces as well as the various contact forces

m_2 = Mass of gear and pinion no. 2

$\bar{A}_{0_2/ground}$ = Acceleration of the component center of mass, i.e., equation D-423

The full force equation is now obtained with the help of figures D-10a and D-10b, as well as equation B-153 of reference 1:

$$- F_{23} \bar{n}_{23} - s_2 \mu F_{23} \bar{n}_{N23} + F_{12} \bar{n}_{12} - \mu s_1 F_{12} \bar{n}_{N12}$$

$$+ F_{x2u} \bar{i} - \mu F_{x2u} \bar{j} + F_{y2u} \bar{j} + \mu F_{y2u} \bar{i} + F_{z2} \bar{k}$$

$$- F_{x2L} \bar{i} + \mu F_{x2L} \bar{j} - F_{y2L} \bar{j} - \mu F_{y2L} \bar{i}$$

$$= m_2 \left(0_x \bar{i} + 0_y \bar{j} + 0_z \bar{k} \right) \tag{D-428}$$

In the above, $\bar{n}_{23}$ and $\bar{n}_{N23}$ are given by equations D-162 and D-163, respectively. The unit vectors $\bar{n}_{12}$ and $\bar{n}_{N12}$ were defined by equations D-308 and D-309. Appropriate substitution and subsequent separation into x and y components furnishes:

X-Component of Gear and Pinion Force Equation

$$- F_{23} \sin \left(\beta_2 + \theta_2\right) - s_2 \mu F_{23} \cos \left(\beta_2 + \theta_2\right) - F_{12} \sin \left(\beta_1 - \theta_1\right)$$

$$+ \mu s_1 F_{12} \cos \left(\beta_1 - \theta_1\right) + F_{x2u} + \mu F_{y2u} - F_{x2L} - \mu F_{y2L} = m_2 0_x \tag{D-429}$$

Y-Component of Gear and Pinion Force Equation

$$F_{23} \cos \left(\beta_2 + \theta_2\right) - \mu s_2 F_{23} \sin \left(\beta_2 + \theta_2\right) + F_{12} \cos \left(\beta_1 - \theta_1\right)$$

$$+ \mu s_1 F_{12} \sin \left(\beta_1 - \theta_1\right) - \mu F_{x2u} + F_{y2u} + \mu F_{x2L} - F_{y2L} = m_2 0_y \tag{D-430}$$

Z-Component of Gear and Pinion Force Equations

This thrust force is best expressed in tilded form, so that,

$$\tilde{F}_{z2} = |m_2 \, O_z| \quad \text{(D-431)}$$

Moment Equations for Gear and Pinion No. 2

Since gear and pinion no. 2 represents a symmetrical body without products of inertia, its moment equations may be expressed in terms of the projectile-fixed X-Y-Z system by the appropriate adaption of equation B-13 (app B).

.. Keeping in mind that the angular velocity $\dot{\phi}_2$ and the angular acceleration $\ddot{\phi}_2$, of gear and pinion no. 2 with respect to the projectile, must be expressed in terms of the escape wheel angular velocity $\dot{\phi}$ and angular acceleration $\ddot{\phi}$,

$$\dot{\phi}_2 = N_{32} \, \dot{\phi} \quad \text{(D-432)}$$

and

$$\ddot{\phi}_2 = N_{32} \, \ddot{\phi} \quad \text{(D-433)}$$

This gives the moment equation the following form (note that the pivot point O_2 and the center of mass C_2 coincide):

$$\begin{aligned} \bar{M}_{O_2} = {} & [I_{x2} \, \dot{\omega}_x + I_{z2} \, \omega_y \, (\omega_z + N_{32} \, \dot{\phi}) - I_{y2} \, \omega_y \, \omega_z] \, \bar{i} \\ & + [I_{y2} \, \dot{\omega}_y + I_{x2} \, \omega_x \, \omega_z - I_{z2} \, \omega_x \, (\omega_z + N_{32} \, \dot{\phi})] \, \bar{j} \\ & + I_{z2} \, (\dot{\omega}_z + N_{32} \, \ddot{\phi}) \, \bar{k} \end{aligned} \quad \text{(D-435)}$$

The moment $\bar{M}_{O_2}$ about point O_2 is now found with the help of the pivot shaft free-body diagram of figure D-10b as well as by the adaptation of terms due to F_{12} and F_{32}, according to equation B-160 of reference 1. Note that the thrust torque (-) $\mu \, \rho_{f2} \, \tilde{F}_{z2} \, \bar{k}$ uses the tilded form of F_{z2} equation D-431 in order to always make this friction moment positive, i.e, oppose the clockwise rotation of the component. The parameter ρ_{f2} represents the thrust friction radius, while ρ_2 is the radius of the pivot shaft. Then

$$\bar{M}_{O_2} = F_{23}\, R_{b2}\, \bar{k} - \mu\, s_2\, F_{23}\, a_2\, \bar{k} - F_{12}\, r_{b2}\, \bar{k} + \mu\, s_1\, F_{12}\, (d_1 - a_1)\, \bar{k}$$

$$+ \mu\, \rho_{f2}\, \tilde{F}_{z2}\, \bar{k} + (L_u\, \bar{k} - \rho_2\, \bar{i}) \times (F_{x2u}\, \bar{i} - \mu\, F_{x2u}\, \bar{j})$$

$$+ (L_u\, \bar{k} - \rho_2\, \bar{j}) \times (F_{y2u}\, \bar{j} + \mu\, F_{y2u}\, \bar{i})$$

$$+ (-L_L\, \bar{k} + \rho_2\, \bar{i}) \times (-F_{x2L}\, \bar{i} + \mu\, F_{x2L}\, \bar{j})$$

$$+ (-L_L\, \bar{k} + \rho_2\, \bar{j}) \times (-F_{y2L}\, \bar{j} - \mu\, F_{y2L}\, \bar{i}) \qquad \text{(D-436)}$$

The above becomes

$$\bar{M}_{O_2} = [\mu\, L_u\, F_{x2u} - L_u\, F_{y2u} + \mu\, L_L\, F_{x2L} - L_L\, F_{y2L}]\, \bar{i}$$

$$+ [L_u\, F_{x2u} + \mu\, L_u\, F_{y2u} + L_L\, F_{x2L} + \mu\, L_L\, F_{y2L}]\, \bar{j}$$

$$+ [F_{23}\, (R_{b2} - \mu\, s_2\, a_2) - F_{12}\, (r_{b2} - \mu\, s_1\, (d_1 - a_1))$$

$$+ \mu\, \rho_{f2}\, \tilde{F}_{z2} + \mu\, \rho_2\, (F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L})]\, \bar{k} \qquad \text{(D-437a)}$$

Substitution of equation D-436 into equation D-434 yields the following moment component expressions:

X-Component of Gear and Pinion Moment Equation

$$\mu\, L_u\, F_{x2u} - L_u\, F_{y2u} + \mu\, L_L\, F_{x2L} - L_L\, F_{y2L}$$

$$= I_{x2}\, \dot{\omega}_x + I_{z2}\, \omega_y\, (\omega_z + N_{32}\, \dot{\phi}) - I_{y2}\, \omega_y\, \omega_z \qquad \text{(D-437b)}$$

Y-Component of Gear and Pinion Moment Equation

$$L_u\, F_{x2u} + \mu\, L_u\, F_{y2u} + L_L\, F_{x2L} + \mu\, L_L\, F_{y2L}$$

$$= I_{y2}\, \dot{\omega}_y + I_{x2}\, \omega_x\, \omega_z - I_{z2}\, \omega_x\, (\omega_z + N_{32}\, \dot{\phi}) \qquad \text{(D-438)}$$

Z-Component of Gear and Pinion Moment Equation

$$F_{23}\left(R_{b2} + \mu\, s_2\, a_2\right) - F_{12}\left(r_{b2} - \mu\, s_1\left(d_1 - a_1\right)\right)$$

$$+ \mu\, \rho_{f2}\, \widetilde{F}_{z2} + \mu\, \rho_2\left(F_{x2u} + F_{y2u} + F_{x2L} + F_{y2L}\right)$$

$$= I_{z2}\left(\dot{\omega}_z + N_{32}\, \ddot{\phi}\right) \quad \text{(D-439)}$$

Simplification of Force Equations for Gear and Pinion No. 2

The X-component of the force equation, i.e., equation D-429, is now rewritten:

$$- F_{x2u} - \mu\, F_{y2u} + F_{x2L} + \mu\, F_{y2L} = A_{84}\, F_{23} + A_{85}\, F_{12} + A_{86} \quad \text{(D-440)}$$

where

$$A_{84} = -\left[\sin\left(\beta_2 + \theta_2\right) + \mu\, s_2 \cos\left(\beta_2 + \theta_2\right)\right] \quad \text{(D-441)}$$

$$A_{85} = -\left[\sin\left(\beta_1 - \theta_1\right) - \mu\, s_1 \cos\left(\beta_1 - \theta_1\right)\right] \quad \text{(D-442)}$$

$$A_{86} = - m_2\, \Omega_x \quad \text{(D-443)}$$

The Y-component of the force expression, i.e., equation D-430 is simplified to:

$$\mu\, F_{x2u} - F_{y2u} - \mu\, F_{x2L} + F_{y2L} = A_{87}\, F_{23} + A_{88}\, F_{12} + A_{89} \quad \text{(D-444)}$$

where

$$A_{87} = -\left[\mu\, s_2 \sin\left(\beta_2 + \theta_2\right) - \cos\left(\beta_2 + \theta_2\right)\right] \quad \text{(D-445)}$$

$$A_{88} = \left[\mu\, s_1 \sin\left(\beta_1 - \theta_1\right) + \cos\left(\beta_1 - \theta_1\right)\right] \quad \text{(D-446)}$$

$$A_{89} = - m_2\, \Omega_y \quad \text{(D-447)}$$

Simplification of Moment Equations for Gear and Pinion No. 2

Equation D-437b for the X-component of the moment may be rewritten as:

$$-\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} = A_{90} + A_{91} \dot{\phi} \quad \text{(D-448)}$$

where

$$A_{90} = -\left[I_{x2} \dot{\omega}_x + \omega_y \omega_z \left(I_{z2} - I_{y2}\right)\right] \quad \text{(D-449)}$$

$$A_{91} = -I_{z2} N_{32} \omega_y \quad \text{(D-450)}$$

Equation D-438 for the Y-component of the moment is written as follows:

$$-L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} = A_{92} + A_{93} \dot{\phi} \quad \text{(D-451)}$$

where

$$A_{92} = -\left[I_{y2} \dot{\omega}_y + \omega_x \omega_z \left(I_{x2} - I_{z2}\right)\right] \quad \text{(D-452)}$$

$$A_{93} = I_{z2} \omega_x N_{32} \quad \text{(D-453)}$$

Equation D-439 for the Z-component of the moment remains as is.

Simultaneous Solution of Pivot Forces of Gear and Pinion No. 2

Equations D-440, D-444, D-448, and D-451 are now solved simultaneously for the pivot forces. Therefore,

$$\left.\begin{aligned} -F_{x2u} - \mu F_{y2u} + F_{x2L} + \mu F_{y2L} &= B_{21} \\ \mu F_{x2u} - F_{y2u} - \mu F_{x2L} + F_{y2L} &= B_{22} \\ -\mu L_u F_{x2u} + L_u F_{y2u} - \mu L_L F_{x2L} + L_L F_{y2L} &= B_{23} \\ -L_u F_{x2u} - \mu L_u F_{y2u} - L_L F_{x2L} - \mu L_L F_{y2L} &= B_{24} \end{aligned}\right\} \quad \text{(D-454)}$$

where

$$B_{21} = A_{84} F_{23} + A_{85} F_{12} + A_{86} \quad \text{(D-455)}$$

$$B_{22} = A_{87}\ F_{23} + A_{88}\ F_{12} + A_{89} \qquad \text{(D-456)}$$

$$B_{23} = A_{90} + A_{91}\ \dot{\phi} \qquad \text{(D-457)}$$

$$B_{24} = A_{92} + A_{93}\ \dot{\phi} \qquad \text{(D-458)}$$

To use the solutions of equation D-67, equation D-454 has to be changed to a form that has the same signs as this set of expressions. This may be accomplished by substituting

$$\mu^* = -\mu \qquad \text{(D-459)}$$

(This replaces $A_{11} = \mu_1\ s_5$ in equation D-67.) Equation D-454 then becomes:

$$\left.\begin{aligned}
&- F_{x2u} + \mu^* F_{y2u} + F_{x2L} - \mu^* F_{y2L} = B_{21} \\
&- \mu^* F_{x2u} - F_{y2u} + \mu^* F_{x2L} + F_{y2L} = B_{22} \\
&\mu^* L_u F_{x2u} + L_u F_{y2u} + \mu^* L_L F_{x2L} + L_L F_{y2L} = B_{23} \\
&- L_u F_{x2u} + \mu^* L_u F_{y2u} - L_L F_{x2L} + \mu^* L_L F_{y2L} = B_{24}
\end{aligned}\right\} \qquad \text{(D-460)}$$

With the above substitution (i.e., equation D-459) the coefficient determinant of equation D-460 becomes according to equation D-75:

$$D = \left[(L_u + L_L)(1 + \mu^2)\right]^2 \qquad \text{(D-461)}$$

According to equation D-80, the determinant D_{Fx2u} now becomes with the appropriate changes:

$$D_{F_{x2u}} = (L_u + L_L)(1 + \mu^2)\left[- L_L\ B_{21} + \mu L_L\ B_{22} - \mu B_{23} - B_{24}\right] \qquad \text{(D-462)}$$

Now substitute for the B_{2i}'s according to equations D-455 to D-458:

$$D_{F_{x2u}} = (L_u + L_L)(1 + \mu^2)\ \{ - L_L\ [A_{84}\ F_{23} + A_{85}\ F_{12} + A_{86}]$$

$$+ \mu L_L\ [A_{87}\ F_{23} + A_{88}\ F_{12} + A_{89}]$$

$$- \mu \left[A_{90} + A_{91} \dot{\phi}\right] - \left[A_{92} + A_{93} \dot{\phi}\right]\} \quad \text{(D-463)}$$

After collecting of terms, the tilded force $\tilde{F}_{x2u}$ becomes:

$$\tilde{F}_{x2u} = \frac{\tilde{D}_{F_{x2u}}}{D} = \frac{1}{L_T \left(1 + \mu^2\right)} \left[C_{57} + C_{58} \dot{\phi} + C_{59} F_{23} + C_{60} F_{12}\right] \quad \text{(D-464)}$$

where

$$C_{57} = \left|- L_L A_{86} + \mu \left(L_L A_{89} - A_{90}\right) - A_{92}\right| \quad \text{(D-465)}$$

$$C_{58} = \left|\mu A_{91} + A_{93}\right| \quad \text{(D-466)}$$

$$C_{59} = \left|L_L \left(\mu A_{87} - A_{84}\right)\right| \quad \text{(D-467)}$$

$$C_{60} = \left|L_L \left(\mu A_{88} - A_{85}\right)\right| \quad \text{(D-468)}$$

According to equation D-90, $D_{F_{y2u}}$ with appropriate changes becomes:

$$D_{F_{y2u}} = \left(L_u + L_L\right)\left(1 + \mu^2\right) \left[- \mu L_L B_{21} - L_L B_{22} + B_{23} - \mu B_{24}\right] \quad \text{(D-469)}$$

Substitution of equations D-455 to D-458 gives:

$$D_{F_{y2u}} = \left(L_u + L_L\right)\left(1 + \mu^2\right) \{ - \mu L_L \left[A_{84} F_{23} + A_{85} F_{12} + A_{86}\right]$$

$$- L_L \left[A_{87} F_{23} + A_{88} F_{12} + A_{89}\right]$$

$$+ \left[A_{90} + A_{91} \dot{\phi}\right] - \mu \left[A_{92} + A_{93} \dot{\phi}\right] \quad \text{(D-470)}$$

After appropriate collecting of terms, the tilded force $\tilde{F}_{y2u}$ becomes:

$$\tilde{F}_{y2u} = \frac{\tilde{D}_{F_{y2u}}}{D} = \frac{1}{L_T \left(1 + \mu^2\right)} \left[C_{61} + C_{62} \dot{\phi} + C_{63} F_{23} + C_{64} F_{12}\right] \quad \text{(D-471)}$$

where

$$C_{61} = |- L_L A_{89} - \mu (L_L A_{86} + A_{92}) + A_{90}| \quad (D\text{-}472)$$

$$C_{62} = |A_{91} - \mu A_{93}| \quad (D\text{-}473)$$

$$C_{63} = |L_L (\mu A_{84} + A_{87})| \quad (D\text{-}474)$$

$$C_{64} = |L_L (\mu A_{85} + A_{88})| \quad (D\text{-}475)$$

According to equation D-100, $D_{F_{x2L}}$ with the applicable changes becomes:

$$D_{F_{x2L}} = (L_u + L_L)(1 + \mu^2) \{L_u B_{21} - \mu L_u B_{22} - \mu B_{23} - B_{24}\} \quad (D\text{-}476)$$

Substitute equations D-455 to D-458:

$$D_{F_{x2L}} = (L_u + L_L)(1 + \mu^2) \{L_u [A_{84} F_{23} + A_{85} F_{12} + A_{86}]$$

$$- \mu L_u [A_{87} F_{23} + A_{88} F_{12} + A_{89}]$$

$$- \mu [A_{90} + A_{91} \dot{\phi}] - [A_{92} + A_{93} \dot{\phi}]\} \quad (D\text{-}477)$$

After collecting of terms, the tilded force F_{x2L} becomes:

$$\tilde{F}_{x2L} = \frac{\tilde{D}_{F_{x2L}}}{D} = \frac{1}{L_T (1 + \mu^2)} [C_{65} + C_{66} \dot{\phi} + C_{67} F_{23} + C_{68} F_{12}] \quad (D\text{-}478)$$

where

$$C_{65} = |- \mu (L_u A_{89} + A_{90}) + L_u A_{86} - A_{92}| \quad (D\text{-}479)$$

$$C_{66} = |\mu A_{91} + A_{93}| \quad (D\text{-}480)$$

$$C_{67} = |L_u (A_{84} - \mu A_{87})| \quad (D\text{-}481)$$

$$C_{68} = |L_u (A_{85} - \mu A_{88})| \quad (D\text{-}482)$$

According to equation D-109, the determinant $D_{F_{y2L}}$ after applicable adaptation becomes:

$$D_{F_{y2L}} = (L_u + L_L)(1 + \mu^2) \{ \mu L_u B_{21} + L_u B_{22} + B_{23} - \mu B_{24} \} \qquad \text{(D-483)}$$

Substitution of equations D-455 to D-458 lead to:

$$D_{F_{y2L}} = (L_u + L_L)(1 + \mu^2) \{ \mu L_u [A_{84} F_{23} + A_{85} F_{12} + A_{86}]$$

$$+ L_u [A_{87} F_{23} + A_{88} F_{12} + A_{89}]$$

$$+ [A_{90} + A_{91} \dot{\phi}] - \mu [A_{92} + A_{93} \dot{\phi}]\} \qquad \text{(D-484)}$$

Again, terms are collected and an expression for the tilded force F_{y2L} is found. Therefore,

$$\tilde{F}_{y2L} = \frac{\tilde{D}_{F_{y2L}}}{D} = \frac{1}{L_T (1 + \mu^2)} [C_{69} + C_{70} \dot{\phi} + C_{71} F_{23} + C_{72} F_{12}] \qquad \text{(D-485)}$$

where

$$C_{69} = |L_u A_{89} + \mu (L_u A_{86} - A_{92}) + A_{90})| \qquad \text{(D-486)}$$

$$C_{70} = |A_{91} - \mu A_{93}| \qquad \text{(D-487)}$$

$$C_{71} = |L_u (\mu A_{84} + A_{87})| \qquad \text{(D-488)}$$

$$C_{72} = |L_u (\mu A_{85} + A_{88})| \qquad \text{(D-489)}$$

Substitution of Tilded Pivot Forces Into Z-Component of Moment Equation

Substitution of equations D-431, D-464, D-471, D-478, and D-485 into the Z-moment equation D-439 is now required. First, let the tilde forces be added:

$$\tilde{F}_{x2u} + \tilde{F}_{y2u} + \tilde{F}_{x2L} + \tilde{F}_{y2L} = A_{94} + A_{95} \dot{\phi} + A_{96} F_{23} + A_{97} F_{12} \qquad \text{(D-490)}$$

where

$$A_{94} = \frac{C_{57} + C_{61} + C_{65} + C_{69}}{L_T \ (1 + \mu^2)} \tag{D-491}$$

$$A_{95} = \frac{C_{58} + C_{62} + C_{66} + C_{70}}{L_T \ (1 + \mu^2)} \tag{D-492}$$

$$A_{96} = \frac{C_{59} + C_{63} + C_{67} + C_{71}}{L_T \ (1 + \mu^2)} \tag{D-493}$$

$$A_{97} = \frac{C_{60} + C_{64} + C_{68} + C_{72}}{L_T \ (1 + \mu^2)} \tag{D-494}$$

Further, let equation D-431 be expressed as

$$\tilde{F}_{z2} = A_{98} = |m_2 \ Q_z| \tag{D-495}$$

Equation D-439 then becomes:

$$\begin{aligned} & F_{23} \ (R_{b2} - \mu \ s_2 \ a_2) - F_{12} \ (r_{b2} \ \mu \ s_1 \ (d_1 - a_1)) \\ & + \mu \ \rho_{f2} \ A_{98} + \mu \ \rho_2 \ [A_{94} \pm A_{95} \ \dot{\phi} + A_{96} \ F_{23} + A_{97} \ F_{12}] \\ & \quad = I_{z2} \ (\dot{\omega}_z + N_{32} \ \ddot{\phi}) \end{aligned} \tag{D-496}$$

or

$$\begin{aligned} & F_{23} \ [R_{b2} - \mu \ s_2 \ a_2 + \mu \ \rho_2 \ A_{96}] - F_{12} \ [r_{b2} - \mu \ s_1 \ (d_1 - a_1) - \mu \ \rho_2 \ A_{97}] \\ & + \mu \ [\rho_{f2} \ A_{98} + \rho_2 \ A_{94}] \pm \mu \ \rho_2 \ A_{95} \ \dot{\phi} = A_{99} + A_{100} \ \ddot{\phi} \end{aligned} \tag{D-497}$$

where

$$A_{99} = I_{z2} \ \dot{\omega}_z \tag{D-498}$$

$$A_{100} = I_{z2} \ N_{32} \tag{D-499}$$

Now consider again the signs of the friction moment terms, recalling that a reversal in the gear train motion will cause a change of the sign of μ in the program. The component rotates normally in a clockwise direction and the friction moments must be positive. Also note that N_{32} is negative.

The following friction moments must be positive for positive rotation $\dot{\phi}$ of the escape wheel. (This implies a negative angular velocity for gear and pinion no. 2.)

$$\mu F_{23} \rho_2 A_{96} \quad (A_{96} \text{ is sum of absolute values}) \tag{D-500}$$

$$\mu F_{12} \rho_2 A_{97} \quad (A_{97} \text{ is sum of absolute values}) \tag{D-501}$$

$$\mu \left[\rho_{f2} A_{98} + \rho_2 A_{94}\right] (A_{94} \text{ and } A_{98} \text{ are absolute values}) \tag{D-502}$$

The sign of the term containing $\dot{\phi}$ must be determined by the sign of $\dot{\phi}$ alone. When $\dot{\phi}$ is positive, the gear and pinion no. 2 turns negatively, and the friction moment must be positive. Therefore, the term must have a positive sign, and the absolute values of μ must be used:

$$+ |\mu| \rho_2 A_{95} \dot{\phi} \tag{D-503}$$

Note that A_{95} is an absolute value.

With the above considerations, equation D-497 becomes:

$$F_{23} \left[R_{b2} - \mu s_2 a_2 + \mu \rho_2 A_{96}\right] - F_{12} \left[r_{b2} - \mu s_1 (d_1 - a_1) - \mu \rho_2 A_{97}\right]$$

$$+ \mu \left[\rho_{f2} A_{98} + \rho_2 A_{94}\right] + |\mu| \rho_2 A_{95} \dot{\phi} = A_{99} + A_{100} \ddot{\phi} \tag{D-504}$$

Finally, the above is solved for F_{23}:

$$F_{23} = \frac{A_{102} F_{12} - A_{103} - A_{104} \dot{\phi} + A_{99} + A_{100} \ddot{\phi}}{A_{101}} \tag{D-505}$$

where

$$A_{101} = R_{b2} - \mu s_2 a_2 + \mu \rho_2 A_{96} \tag{D-506}$$

$$A_{102} = r_{b2} - \mu s_1 (d_1 - a_1) - \mu \rho_2 A_{97} \tag{D-507}$$

$$A_{103} = \mu \left[\rho_{f2} A_{98} + \rho_2 A_{94}\right] \qquad \text{(D-508)}$$

$$A_{104} = |\mu| \rho_2 A_{95} \qquad \text{(D-509)}$$

Dynamics of Combined System in Coupled Motion (Applicable to Both Configurations)

As in reference 1, it is now necessary to develop a single differential equation for coupled motion. This is accomplished by first substituting equation D-411 for F_{12} into equation D-505 for F_{23}. The latter expression is then made part of the combined differential equation for the escapement, i.e., equation D-240 or D-278. Therefore substitution of equation D-411 into equation D-505 gives:

$$F_{23} = \frac{1}{A_{101}} \left\{\frac{A_{102}}{A_{79}} \left[- I_{1R} \ddot{\phi} - A_{81} \dot{\phi} - A_{82} \dot{\phi}^2 - A_{80}\right.\right.$$

$$\left. - A_{60} + m_1 r_{c1} \left(O_x \sin \gamma - O_y \cos \gamma\right)\right]$$

$$\left. - A_{103} - A_{104} \dot{\phi} + A_{99} + A_{100} \ddot{\phi}\right\} \qquad \text{(D-510)}$$

or

$$F_{23} = \frac{1}{A_{101}} \left\{ \ddot{\phi} \left[- \frac{A_{102}}{A_{79}} I_{1R} + A_{100}\right] - \dot{\phi} \left[\frac{A_{102} A_{81}}{A_{79}} + A_{104}\right]\right.$$

$$+ \dot{\phi}^2 \left[- \frac{A_{102} A_{82}}{A_{79}}\right] + \left[- \frac{(A_{80} + A_{60}) A_{102}}{A_{79}} - A_{103} + A_{99}\right]$$

$$\left. + \frac{A_{102}}{A_{79}} m_1 r_{c1} \left(O_x \sin \gamma - O_y \cos \gamma\right)\right\} \qquad \text{(D-511)}$$

The above is now substituted into equation D-240

$$[A_{51}\ I_{PR}\ U - A_{29}\ I_{zs}]\ \ddot{\phi} + [A_{51}\ (A_{32}\ U^2 + I_{PR}\ V) - A_{29}\ A_{48}]\ \dot{\phi}^2$$

$$+ A_{51}\ A_{31}\ U\ \dot{\phi} = \frac{A_{29}\ A_{49}}{A_{101}} \{[A_{100} - \frac{A_{102}\ I_{1R}}{A_{79}}]\ \ddot{\phi}$$

$$- [\frac{A_{102}\ A_{81}}{A_{79}} + A_{104}]\ \dot{\phi} - \frac{A_{102}\ A_{82}}{A_{79}}\ \dot{\phi}^2 - [\frac{A_{102}\ (A_{80} + A_{60})}{A_{79}}$$

$$+ A_{103} - A_{99}] + \frac{A_{102}}{A_{79}}\ m_1\ r_{cl}\ (O_x\ \sin\gamma - O_y\ \cos\gamma)\}$$

$$+ A_{29}\ A_{50} - A_{51}\ (A_9 + A_{30}) + A_{51}\ m_p\ r_{cp}\ (K_x\ \sin\beta - K_y\ \cos\beta) \qquad \text{(D-512)}$$

Finally, the above becomes*

$$A_{105}\ \ddot{\phi} + A_{106}\ \dot{\phi}^2 + A_{107}\ \dot{\phi}$$

$$= A_{108} + A_{109}\ [O_x\ \sin\gamma - O_y\ \cos\gamma]$$

$$+ A_{110}\ [K_x\ \sin\beta - K_y\ \cos\beta] \qquad \text{(D-513)}$$

where

$$A_{105} = A_{51}\ I_{PR}\ U - A_{29}\ I_{zs} - \frac{A_{29}\ A_{49}\ A_{100}}{A_{101}} + \frac{A_{29}\ A_{49}\ A_{102}}{A_{101}\ A_{79}}\ I_{1R} \qquad \text{(D-514)}$$

$$A_{106} = A_{51}\ (A_{32}\ U^2 + I_{PR}\ V) - A_{29}\ A_{48} + \frac{A_{29}\ A_{49}\ A_{102}\ A_{82}}{A_{101}\ A_{79}} \qquad \text{(D-515)}$$

$$A_{107} = A_{51}\ A_{31}\ U + \frac{A_{29}\ A_{49}}{A_{101}}\ (\frac{A_{102}\ A_{81}}{A_{79}} + A_{104}) \qquad \text{(D-516)}$$

---

* The value of the signum function s_7 decides whether entrance- or exit-coupled motion is described by the differential equation D-513.

$$A_{108} = - \frac{A_{29} A_{49}}{A_{101}} \left[\frac{A_{102} (A_{80} + A_{60})}{A_{79}} + A_{103} - A_{99}\right]$$

$$+ A_{29} A_{50} - A_{51} (A_9 + A_{30}) \quad \text{(D-517)}$$

$$A_{109} = \frac{A_{29} A_{49} A_{102}}{A_{101} A_{79}} m_1 r_{cl} \quad \text{(D-518)}$$

$$A_{110} = A_{51} m_p r_{cp} \quad \text{(D-519)}$$

Contact Forces for Coupled Motion

The contact force F_{23} is given by equation D-511:

$$F_{23} = \frac{A_{111} \ddot{\phi} + A_{112} \dot{\phi}^2 + A_{113} \dot{\phi} + A_{114}}{A_{101}} \quad \text{(D-520)}$$

where

$$A_{111} = - \frac{A_{102} I_{1R}}{A_{79}} + A_{100} \quad \text{(D-521)}$$

$$A_{112} = - \frac{A_{102} A_{82}}{A_{79}} \quad \text{(D-522)}$$

$$A_{113} = - \left(\frac{A_{102} A_{81}}{A_{79}} + A_{104}\right) \quad \text{(D-523)}$$

$$A_{114} = - \frac{(A_{80} + A_{60}) A_{102}}{A_{79}} - A_{103} + A_{99}$$

$$+ \frac{A_{102}}{A_{79}} m_1 r_{cl} \left[0_x \sin \gamma - 0_y \cos \gamma\right] \quad \text{(D-524)}$$

The contact force F_{12} is found with the help of equation D-505:

$$F_{12} = \frac{F_{23} A_{101} + A_{115} + A_{104} \dot{\phi} - A_{100} \ddot{\phi}}{A_{102}} \quad \text{(D-525)}$$

where

$$A_{115} = A_{103} - A_{99} \tag{D-526}$$

The contact force P_n, between verge and escape wheel, may either be obtained from equation D-137 or from equation D-235. Therefore, from equation D-137 with the pallet variable ψ:

$$P_n = \frac{1}{A_{29}} \left[I_{PR} \ddot{\psi} + A_{31} \dot{\psi} + A_{32} \dot{\psi}^2 + A_{116} - m_p r_{cp} \left(K_x \sin \beta - K_y \cos \beta \right) \right] \tag{D-527}$$

where

$$A_{116} = A_9 + A_{30} \tag{D-528}$$

In terms of the escape wheel variable ϕ, equation D-235 gives:

$$P_n = \frac{I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + F_{23} A_{49} + A_{50}}{A_{51}} \tag{D-529}$$

Equations D-527 and D-529 are valid both for entrance- and exit-coupled motion as long as the common expressions for A_{29} and A_{51} are used (eqs D-278 to D-283).

Differential Equations and Contact Forces During Free Motion

Pallet Free Motion Differential Equation

By letting $P_n = 0$ in equation D-527, the free motion equation of the pallet is obtained, which is now independent of entrance or exit conditions:

$$I_{PR} \ddot{\psi} + A_{32} \dot{\psi}^2 + A_{31} \dot{\psi} = - A_{116} + m_p r_{cp} \left[K_x \sin \beta - K_y \cos \beta \right] \tag{D-530}$$

Escape Wheel-Gear Train-Rotor Free Motion Differential Equation

First let P_n be set equal to zero in equation D-529. This results in:

$$I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 = - A_{49} F_{23} - A_{50} \tag{D-531}$$

Note that this is also now independent of entrance or exit condition.

Now, F_{23} (eq D-520) is substituted into the above expression. This leads to:

$$A_{117} \ddot{\phi} + A_{118} \dot{\phi}^2 + A_{119} \dot{\phi} = A_{120} \qquad \text{(D-532)}$$

where

$$A_{117} = I_{zs} + \frac{A_{49} A_{111}}{A_{101}} \qquad \text{(D-533)}$$

$$A_{118} = A_{48} + \frac{A_{49} A_{112}}{A_{101}} \qquad \text{(D-534)}$$

$$A_{119} = \frac{A_{49} A_{113}}{A_{101}} \qquad \text{(D-535)}$$

$$A_{120} = -\left(A_{50} + \frac{A_{49} A_{114}}{A_{101}}\right) \qquad \text{(D-536)}$$

Contact Forces During Free Motion

Equation D-531 may be solved for the free motion contact force F_{F23} once $\ddot{\phi}$ and $\dot{\phi}$, for free motion, are known:

$$F_{F23} = \frac{-\left(I_{zs} \ddot{\phi} + A_{48} \dot{\phi}^2 + A_{50}\right)}{A_{49}} \qquad \text{(D-537)}$$

(The additional subscript F stands for free motion.)

Equation D-505 was derived for gear and pinion set no. 2. It may now be modified to obtain the free motion contact force F_{F12}, using free motion values of F_{F23}, $\ddot{\phi}$, and $\dot{\phi}$:

$$F_{F12} = \frac{F_{F23} A_{101} + A_{103} + A_{104} \dot{\phi} - A_{99} - A_{100} \ddot{\phi}}{A_{102}} \qquad \text{(D-538)}$$

Finally, with equation D-526:

$$F_{F12} = \frac{F_{F23}\, A_{101} + A_{115} + A_{104}\, \dot{\phi} - A_{100}\, \ddot{\phi}}{A_{102}} \tag{D-539}$$

Impact Equations

The impact equations may be taken directly from reference 1 if care is taken to adjust all parameters to the present notation. Just as in reference 1, only the kinematics relative to the fuze body counts, since all other angular velocities are common to both pallet and escape wheel.

For entrance impact the angle α_{EN} must be used, while for exit impact time the angle α_{EX} is applicable. Entrance and exit impact equations are identical (ref 1). Therefore,

$$\dot{\phi}_f = \frac{\dot{\phi}_i\, \left(I_{STOT}\, D_1'^{\,2} - e_r\, I_{\zeta\zeta_p}\, A_1'^{\,2}\right) + \dot{\psi}_i\, I_{\zeta\zeta_p}\, A_1'\, \left(1 + e_r\right) D_1'}{I_{\zeta\zeta_p}\, A_1'^{\,2} + I_{STOT}\, D_1'^{\,2}} \tag{D-540}$$

$$\dot{\psi}_f = \frac{\dot{\phi}_f\, A_1' - e_r\, \left(\dot{\psi}_i\, D_1' - \dot{\phi}_i\, A_1'\right)}{D_1'} \tag{D-541}$$

where

$$I_{STOT} = I_{zs} + I_{z2}\, N_{32}^2 + I_{\zeta\zeta_1}\, N_{31}^2 \tag{D-542}$$

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APPENDIX E

PROJECTILE KINEMATICS

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Until the time when actual aeroballistic data can be incorporated into program SAEROV, the following expressions for the projectile kinematics will be used:*

Spin Simulation

Assuming a constant spin velocity, obtain for the spin kinematics:

$$\ddot{\phi}_E = 0 \tag{E-1}$$

$$\dot{\phi}_E = \text{DPHIE} = \frac{\text{RPM} \times 2\pi}{60} \tag{E-2}$$

and

$$\phi_E = \text{PHIE} = \dot{\phi}_E \, t \tag{E-3}$$

Precession Simulation

Assuming that the precession velocity is also constant, the following is obtained:

$$\ddot{\psi}_E = 0 \tag{E-4}$$

where

$$\dot{\psi}_E = \text{DPSIE} = \frac{\text{DPHIE}}{\text{KP}} \tag{E-5}$$

KP = K_p, is a divisor to obtain the precession velocity as a fraction of the spin velocity

$$K_p \approx 100 \tag{E-6}$$

$$\psi_E = \text{PSIE} = \dot{\psi}_E \, t \tag{E-7}$$

---

* For nomenclature see appendix A.

Nutation Simulation

The nutation angle is assumed to vary sinusoidally about some initial angle. Then

$$\theta_E = \text{THET} = \text{THETIN} + \text{TVAR} \sin\left(K_n \dot{\psi}_E t\right) \qquad \text{(E-8)}$$

where

THETIN	≈ 8 degrees, the initial cone angle	(E-9)
TVAR	≈ 2 degrees, the maximum change in cone angle	(E-10)
K_n	≈ 6 to 8, multiplier of precession angular velocity $\dot{\psi}_E$ to obtain maximum nutation velocity $\dot{\theta}_{EMAX}$	(E-11)

With the above

$$\dot{\theta}_E = \text{TVAR} * K_n * \dot{\psi}_E \cos\left(K_n \dot{\psi}_E t\right) \qquad \text{(E-12)}$$

$$\ddot{\theta}_E = -\text{TVAR} * K_n^{\,2} * \dot{\psi}_E^{\,2} \sin\left(K_n \dot{\psi}_E t\right) \qquad \text{(E-13)}$$

Drag Deceleration

The deceleration $\ddot{\bar{z}} = \ddot{z}\bar{k}$ of the center of mass, due to drag and expressed in the projectile-fixed system, is given by

$$\ddot{z} = \text{DDZ} = -386.4 * 10 \qquad \text{(E-14)}$$

APPENDIX F

COMPUTER PROGRAM SAEROV

```
      PROGRAM SAEROV(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)             A   1
      COMMON A,B,C,R,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IE A   2
     1ZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,RZ, A   3
     2EREST,LAMBDA,DELTA,PHITOT,PHIPR,N31,N32,OMEGA,OM2,RC1,PHI1C,TEST1, A   4
     3TEST2,NG1,NG2,NP2,NP3,CAPRB1,CAPRB2,RB2,RB3,THETA1,THETA2,R1,R2,R3 A   5
     4,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,GAMMA3,GAMA4P,GAMMA4,G A   6
     5AMAPP,DELTA2,DELTA3,DELTA4,BETA1,BETA2,BETA3,D1,D2,AL1IN,AL1FIN,AL A   7
     62IN,AL2FIN,ALPHA1,ALPHA2,IN,MU,MU1,RCP,PSIC,S1,S2,S4,S5,A1,A2,DPHI A   8
     72,DPSI2,F23MAX,F12MAX,FF23MAX,FF12MAX,PNMAX,PN,ALPHEN,ALPHEX,LL,LU A   9
     8,RHOF,RHOF1,RHOF2,RHOF3,S6                                         A  10
      COMMON /DATA/ RPM                                                 A  11
      COMMON /ZETA/ PSI,TIME,G,DPSI,GP,PHICUTD                          A  12
      DIMENSION AUX(8,2), AUX2(8,4), PRMT(5), PHI(2), DPHI(2), X(4), DX( A  13
     14)                                                                 A  14
      REAL M1,M2,M3,MP,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,IXS,IYS A  15
     1,IZS,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,N31,N32,MU,MU1,LU,LL,LAMBDA,NG1 A  16
     2,NG2,NP2,NP3,N,NT                                                  A  17
      EXTERNAL FCT,OUTP,FCTF,OUTPF                                      A  18
C                                                                       A  19
C     READ IN AND WRITE DATA                                            A  20
C                                                                       A  21
      READ (5,27) A,B,C,ALPHEN,ALPHEX,NT,CONFIG                         A  22
      WRITE (6,28) A,B,C,ALPHEN,ALPHEX,NT,CONFIG                        A  23
      READ (5,29) EREST,LAMBDA,N                                        A  24
      WRITE (6,30) EREST,LAMBDA,N                                       A  25
      READ (5,31) M1,M2,M3,MP                                           A  26
      WRITE (6,32) M1,M2,M3,MP                                          A  27
      READ (5,17) IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1                         A  28
      WRITE (6,18) IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1                        A  29
      READ (5,19) IX2,IY2,IZ2                                           A  30
      WRITE (6,20) IX2,IY2,IZ2                                          A  31
      READ (5,19) IXS,IYS,IZS                                           A  32
      WRITE (6,21) IXS,IYS,IZS                                          A  33
      READ (5,17) IXXP,IEEP,IZZP,IXEP,IZXP,IEZP                         A  34
      WRITE (6,22) IXXP,IEEP,IZZP,IXEP,IZXP,IEZP                        A  35
      READ (5,33) RC1,RCP,RHOP,RPM,PHI1CD,PSICCD,PHID,PHICUTD,MU,MU1    A  36
      WRITE (6,34) RC1,RCP,RHOP,RPM,PHI1CD,PSICCD,PHID,PHICUTD,MU,MU1   A  37
      READ (5,23) LU,LL                                                 A  38
      WRITE (6,24) LU,LL                                                A  39
      READ (5,35) PSUBD1,PSUBD2,NG1,NG2,NP2,NP3,CAPRP1,CAPRP2,RP2,RP3,TH A  40
     1ETA1,THETA2                                                        A  41
      WRITE (6,38) PSUBD1,PSUBD2,NG1,NG2,NP2,NP3,CAPRP1,CAPRP2,RP2,RP3,T A  42
     1HETA1,THETA2                                                       A  43
      READ (5,36) R1,R2,R3,R4                                           A  44
      WRITE (6,39) R1,R2,R3,R4                                          A  45
      READ (5,29) RHO1,RHO2,RHO3                                        A  46
      WRITE (6,40) RHO1,RHO2,RHO3                                       A  47
      READ (5,36) RHOF1,RHOF2,RHOF3,RHOF                                A  48
      WRITE (6,25) RHOF1,RHOF2,RHOF3,RHOF                               A  49
      READ (5,36) CAPRB1,CAPRB2,RB2,RB3                                 A  50
      WRITE (6,41) CAPRB1,CAPRB2,RB2,RB3                                A  51
      READ (5,36) CAPRO1,CAPRO2,RO2,RO3                                 A  52
      WRITE (6,42) CAPRO1,CAPRO2,RO2,RO3                                A  53
      READ (5,37) J1,J2                                                 A  54
      WRITE (6,43) J1,J2                                                A  55
      READ (5,29) RX,RY,RZ                                              A  56
      WRITE (6,26) RX,RY,RZ                                             A  57
```

```
C
C     INITIALIZATION OF PARAMETERS AND CONVERSION TO RADIANS
C
      TIME=0.
      PHITOT=0.
      PHIPR=PHID
      DPHI2=0.
      DPSI2=0.
      F23MAX=0.
      F12MAX=0.
      FF23MAX=0.
      FF12MAX=0.
      PNMAX=0.
      PI=3.14159
      ZZ=PI/180.
      OMEGA=RPM*2.*PI/60.
      OM2=OMEGA*OMEGA
      PHI1C=PHI1CD*ZZ
      PSICC=PSICCD*ZZ
      PSIC=PSICC
      ALPHEN=ALPHEN*ZZ
      ALPHEX=ALPHEX*ZZ
      DELTA=360./N
C
C     COMPUTATION OF GEAR RATIOS
C
      N31=NP2*NP3/(NG1*NG2)
      N32=-NP3/NG2
C
C     DETERMINATION OF SIGNUM FUNCTION S6
C
      IF (CONFIG.EQ.1.) S6=1.
      IF (CONFIG.EQ.2.) S6=-1.
C
C     COMPUTATION OF GAMMAS AND BETAS
C
      GAMMA2=S6*ACOS((R1*R1+R2*R2-(CAPRP1+RP2)**2)/(2.*R1*R2))
      GAMA3P=ACOS((R2*R2+R3*R3-(CAPRP2+RP3)**2)/(2.*R2*R3))
      GAMMA3=GAMMA2+S6*GAMA3P
      GAMA4P=ACOS((R3*R3+R4*R4-A*A)/(2.*R3*R4))
      GAMMA4=GAMMA3+S6*GAMA4P
      GAMMA2D=GAMMA2/ZZ
      GAMMA3D=GAMMA3/ZZ
      GAMMA4D=GAMMA4/ZZ
      DELTA2=ACOS(((CAPRP1+RP2)**2+R1*R1-R2*R2)/(2.*R1*(CAPRP1+RP2)))
      DELTA3=ACOS(((CAPRP2+RP3)**2+R2*R2-R3*R3)/(2.*R2*(CAPRP2+RP3)))
      DELTA4=ACOS((A*A+R3*R3-R4*R4)/(2.*A*R3))
      BETA1=PI-S6*DELTA2
      BETA2=GAMMA2+PI-S6*DELTA3
      BETA3=GAMMA3+PI-S6*DELTA4
      IF (CONFIG.EQ.1.) GAMAPP=DELTA4+GAMA4P
      IF (CONFIG.EQ.2.) GAMAPP=2.*PI-DELTA4-GAMA4P
      BETA1D=BETA1/ZZ
      BETA2D=BETA2/ZZ
      BETA3D=BETA3/ZZ
      WRITE (6,44) BETA1D,BETA2D,BETA3D,GAMMA2D,GAMMA3D,GAMMA4D
C
```

```
      C     CONVERSION OF PRESSURE ANGLES TO RADIANS                     A 115
      C                                                                  A 116
            THETA1=THETA1*ZZ                                             A 117
            THETA2=THETA2*ZZ                                             A 118
      C                                                                  A 119
      C     DETERMINATION OF GEAR TRAIN CONSTANTS                        A 120
      C                                                                  A 121
            TEST1=TAN(THETA1)                                            A 122
            TEST2=TAN(THETA2)                                            A 123
            D1=(CAPRB1+RB2)*TAN(THETA1)                                  A 124
            D2=(CAPRB2+RB3)*TAN(THETA2)                                  A 125
      C                                                                  A 126
      C     DETERMINATION OF EARLIEST AND LATEST POSSIBLE VALUES OF ALPHAS A 127
      C                                                                  A 128
            CALL ALFA (CAPRB1,RB2,THETA1,CAPRO1,RO2,AL1IN,AL1FIN)        A 129
            CALL ALFA (CAPRB2,RB3,THETA2,CAPRO2,RO3,AL2IN,AL2FIN)        A 130
      C                                                                  A 131
      C     INITIALIZATION OF ALPHAS                                     A 132
      C                                                                  A 133
            ALPHA1=AL1IN+(AL1FIN-AL1IN)*J1                               A 134
            ALPHA2=AL2IN+(AL2FIN-AL2IN)*J2                               A 135
      C                                                                  A 136
      C     DATA FOR RUNGE KUTTA                                         A 137
      C                                                                  A 138
            ALPHR=ALPHEN                                                 A 139
            PRMT(2)=3.                                                   A 140
            PRMT(4)=.01                                                  A 141
            NDIM=2                                                       A 142
            NDIM2=4                                                      A 143
            PHI(1)=PHID*ZZ                                               A 144
            PHI(2)=0.                                                    A 145
      C                                                                  A 146
      C     COUPLED MOTION                                               A 147
      C                                                                  A 148
          1 PRMT(1)=TIME                                                 A 149
            PRMT(3)=.00001                                               A 150
            DPHI(1)=.5                                                   A 151
            DPHI(2)=.5                                                   A 152
            IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 2               A 153
            WRITE (6,45)                                                 A 154
          2 CALL RKGS (PRMT,PHI,DPHI,NDIM,IHLF,FCT,OUTP,AUX)             A 155
            IF (PHITOT.GT.PHICUTD) GO TO 16                              A 156
      C                                                                  A 157
      C     TEST FOR ENTRANCE OR EXIT ACTION                             A 158
      C                                                                  A 159
            IF (PN.LE.0.) GO TO 5                                        A 160
            PHID=PHI(1)/ZZ                                               A 161
            IF (PHID.GE.130.00.AND.PHID.LE.160.) GO TO 3                 A 162
            GO TO 4                                                      A 163
          3 PHI(1)=PHI(1)+DELTA*ZZ*NT                                    A 164
            PHIPR=PHI(1)/ZZ                                              A 165
            PSI=PSI+2.*PI-LAMBDA*ZZ                                      A 166
            PSIC=PSICC+LAMBDA*ZZ                                         A 167
            ALPHR=ALPHEX                                                 A 168
            GO TO 5                                                      A 169
          4 PHI(1)=PHI(1)-DELTA*ZZ*(NT+1.)                               A 170
            PHIPR=PHI(1)/ZZ                                              A 171
```

```
      PSI=PSI-2.*PI+LAMBDA*ZZ
      ALPHR=ALPHEN
      PSIC=PSICC
C
C     FREE MOTION
C
    5 PRMT(1)=TIME
      X(1)=PHI(1)
      X(2)=PHI(2)
      X(3)=PSI
      X(4)=DPSI
      DX(1)=.25
      DX(2)=.25
      DX(3)=.25
      DX(4)=.25
      PRMT(3)=.00001
      IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 6
      WRITE (6,46)
    6 CALL RKGS (PRMT,X,DX,NDIM2,IHLF,FCTF,OUTPF,AUX2)
      IF (PHITOT.GT.PHICUTD) GO TO 16
      PHI(1)=X(1)
      PHI(2)=X(2)
      PSI=X(3)
      DPSI=X(4)
      G=(B*SIN(PHI(1))-C*SIN(PSI))/SIN(PSI+ALPHR)
      PHID=PHI(1)/ZZ
      IF (PHID.LT.160..AND.GP.GT.O.) GO TO 10
      IF (PHID.GT.160..AND.GP.LT.O.) GO TO 8
      IF (PHID.LT.160.) GO TO 7
      PHI(1)=PHI(1)-DELTA*ZZ*(NT+1.)
      PHIPR=PHI(1)/ZZ
      PSI=PSI-2.*PI+LAMBDA*ZZ
      PSIC=PSICC
      GO TO 5
    7 PHI(1)=PHI(1)+DELTA*ZZ*NT
      PHIPR=PHI(1)/ZZ
      PSI=PSI+2.*PI-LAMBDA*ZZ
      PSIC=PSICC+LAMBDA*ZZ
      GO TO 5
C
C     EXIT ACTION
C
C     COMPUTATION OF VELOCITIES VP AND VS FOR EXIT ACTION
C
    8 VP=DPSI*(C*COS(ALPHR)+G)
      VS=PHI(2)*B*COS(PHI(1)-PSI-ALPHR)
      IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 9
      WRITE (6,47) VP,VS
C
C     EXIT ACTION TESTS
C
    9 IF (PHI(2).GE.O..AND.DPSI.GE.O.) GO TO 12
      IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 5
      IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 12
      IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
      IF (PHI(2).LE.O..AND.DPSI.GE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 12
      IF (PHI(2).LE.O..AND.DPSI.GE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 5
```

```
      IF (PHI(2).LE.O..AND.DPSI.GE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
      IF (PHI(2).LE.O..AND.DPSI.LE.O.) GO TO 5
C
C     COMPUTATION OF VELOCITIES VP AND VS FOR ENTRANCE ACTION
C
   10 VP=DPSI*(C*COS(ALPHR)+G)
      VS=PHI(2)*B*COS(PHI(1)-PSI-ALPHR)
      IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 11
      WRITE (6,47) VP,VS
C
C     ENTRANCE ACTION
C
   11 IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 5
      IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
      IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 12
      IF (PHI(2).LE.O..AND.DPSI.GE.O.) GO TO 5
      IF (PHI(2).GE.O..AND.DPSI.LE.O.) GO TC 12
      IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 5
      IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 12
      IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
C
C     IMPACT
C
   12 CALL IMPACT (PHI(1),PHI(2),PSI,DPSI)
      IF (TIME.GT.5.0) GO TO 16
C
C     TEST FOR EXIT ACTION
C
      PHID=PHI(1)/ZZ
      IF (PHID.LE.160.0) GO TO 14
C
C     EXIT ACTION
C
C     COMPUTATION OF VELOCITIES VP AND VS FOR EXIT ACTION
      VP=DPSI*(C*COS(ALPHR)+G)
      VS=PHI(2)*B*COS(PHI(1)-PSI-ALPHR)
      IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 13
      WRITE (6,47) VP,VS
   13 IF (ABS(ABS(VP)-ABS(VS)).LT.2.0) GO TO 1
C
C     EXIT ACTION TESTS
C
      IF (PHI(2).GE.O..AND.DPSI.GE.O.) GO TO 1
      IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 5
      IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 1
      IF (PHI(2).GE.O..AND.DPSI.LE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
      IF (PHI(2).LE.O..AND.DPSI.GT.O..AND.ABS(VP).LT.ABS(VS)) GO TO 5
      IF (PHI(2).LE.O..AND.DPSI.GT.O..AND.ABS(VP).GT.ABS(VS)) GO TO 1
      IF (PHI(2).LE.O..AND.DPSI.GT.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
      IF (PHI(2).LE.O..AND.DPSI.LE.O.) GO TO 5
C
C     COMPUTATION OF VELOCITIES VP AND VS FOR ENTRANCE ACTION
C
   14 VP=DPSI*(C*COS(ALPHR)+G)
      VS=PHI(2)*B*COS(PHI(1)-PSI-ALPHR)
      IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 15
      WRITE (6,47) VP,VS
```

```
   15 IF (ABS(ABS(VP)-ABS(VS)).LT.2.0) GO TO 1
C
C     ENTRANCE ACTION TESTS
C
      IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 5
      IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 1
      IF (PHI(2).GE.O..AND.DPSI.GE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
      IF (PHI(2).LE.O..AND.DPSI.GE.O.) GO TO 5
      IF (PHI(2).GE.O..AND.DPSI.LE.O.) GO TO 1
      IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).GT.ABS(VS)) GO TO 1
      IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).LT.ABS(VS)) GO TO 5
      IF (PHI(2).LE.O..AND.DPSI.LE.O..AND.ABS(VP).EQ.ABS(VS)) GO TO 1
   16 TURNS=RPM*TIME/60.
      WRITE (6,48) F23MAX,F12MAX,FF23MAX,FF12MAX,PNMAX,TURNS
      STOP
C
C
C
   17 FORMAT (6E12.4)
   18 FORMAT (1H ,5X,6HIXX1 =,E13.4,3X,6HIEE1 =,E13.4,3X,6HIZZ1 =,E13.4,
     13X,6HIXE1 =,E13.4,3X,6HIZX1 =,E13.4,3X,6HIEZ1 =,E13.4/)
   19 FORMAT (3E12.4)
   20 FORMAT (1H ,5X,5HIX2 =,E13.4,3X,5HIY2 =,E13.4,3X,5HIZ2 =,E13.4/)
   21 FORMAT (1H ,5X,5HIXS =,E13.4,3X,5HIYS =,E13.4,3X,5HIZS =,E13.4/)
   22 FORMAT (1H ,5X,6HIXXP =,E13.4,3X,6HIEEP =,E13.4,3X,6HIZZP =,E13.4,
     13X,6HIXEP =,E13.4,3X,6HIZXP =,E13.4,3X,6HIEZP =,E13.4/)
   23 FORMAT (2F10.5)
   24 FORMAT (6X,4HLU =,F5.3,3X,4HLL =,F5.3/)
   25 FORMAT (6X,7HRHOF1 =,F6.4,3X,7HRHOF2 =,F6.4,3X,7HRHOF3 =,F6.4,3X,6
     1HRHOF =,F6.4/)
   26 FORMAT (6X,4HRX =,F8.3,3X,4HRY =,F8.3,3X,4HRZ =,F8.3/)
   27 FORMAT (7F10.5)
   28 FORMAT (1H1,5X,2HA=,F13.5,5X,2HB=,F13.5,5X,2HC=,F13.5,5X,7HALPHEN=
     1,F9.4,5X,7HALPHEX=,F9.4//6X,3HNT=,F3.0,5X,8HCONFIG =,F3.0/)
   29 FORMAT (3F10.5)
   30 FORMAT (1H ,5X,6HEREST=,F5.2,3X,7HLAMBDA=,F8.3,3X,3HN =,F4.0/)
   31 FORMAT (4E12.5)
   32 FORMAT (1H ,5X,4HM1 =,E15.5,3X,4HM2 =,E15.5,3X,4HM3 =,E15.5,3X,4HM
     1P =,E15.5/)
   33 FORMAT (7F10.4/3F10.4)
   34 FORMAT (6X,5HRC1 =,F7.4,3X,5HRCP =,F7.4,3X,6HRHOP =,F7.4,3X,5HRPM
     1=,F6.0,3X,8HPHI1CD =,F9.4,3X,8HPSICCD =,F9.4,3X,6HPHID =,F9.4//6X,
     29HPHICUTD =,F6.0//6X,4HMU =,F4.2,3X,5HMU1 =,F4.2/)
   35 FORMAT (2F10.4/4F10.0/4F10.5/2F10.4)
   36 FORMAT (4F10.4)
   37 FORMAT (2F10.2)
   38 FORMAT (1H ,5X,8HPSUBD1 =,F5.1,3X,8HPSUBD2 =,F5.1//6X,5HNG1 =,F4.0
     1,3X,5HNG2 =,F4.0,3X,5HNP2 =,F4.0,3X,5HNP3 =,F4.0//6X,8HCAPRP1 =,F8
     2.5,3X,8HCAPRP2 =,F8.5//6X,5HRP2 =,F8.5,3X,5HRP3 =,F8.5//6X,8HTHETA
     31 =,F8.3,3X,8HTHETA2 =,F8.3/)
   39 FORMAT (6X,4HR1 =,F7.5,3X,4HR2 =,F7.5,3X,4HR3 =,F7.5,3X,4HR4 =,F7.
     15/)
   40 FORMAT (6X,6HRHO1 =,F7.5,3X,6HRHO2 =,F7.5,3X,6HRHO3 =,F7.5/)
   41 FORMAT (6X,8HCAPRB1 =,F7.5,3X,8HCAPRB2 =,F7.5,3X,5HRB2 =,F7.5,3X,5
     1HRB3 =,F7.5/)
   42 FORMAT (6X,8HCAPRO1 =,F7.5,3X,8HCAPRO2 =,F7.5,3X,5HRO2 =,F7.5,3X,5
     1HRO3 =,F7.5/)
```

```
   43 FORMAT (1H ,5X,4HJ1 =,F4.2,3X,4HJ2 =,F4.2/)                        A 343
   44 FORMAT (6X,8HBETA1D =,F7.2,3X,8HBETA2D =,F7.2,3X,8HBETA3D =,F7.2/6  A 344
     1X,9HGAMMA2D =,F7.2,3X,9HGAMMA3D =,F7.2,3X,9HGAMMA4D =,F7.2)         A 345
   45 FORMAT (1HO,5X,14HCOUPLED MOTION)                                  A 346
   46 FORMAT (1HO,5X,11HFREE MOTION//)                                   A 347
   47 FORMAT (4HOVP=,F8.3,3X,3HVS=,F8.3)                                 A 348
   48 FORMAT (1HO,6X,8HF23MAX =,F6.2/1HO,6X,8HF12MAX =,F6.2/1HO,6X,9HFF2  A 349
     13MAX =,F6.2/1HO,6X,9HFF12MAX =,F6.2/1HO,6X,7HPNMAX =,F6.2//6X,23HN  A 350
     2UMBER OF TURNS TO ARM=,F8.3)                                       A 351
      END                                                                A 352-
```

```
      SUBROUTINE ALFA (CAPRB,RB,THETA,CAPRO,RO,ALIN,ALFIN)          B   1
C                                                                   B   2
C     THIS SUBROUTINE COMPUTES THE INITIAL AND FINAL VALUES OF ALPHAS   B   3
C                                                                   B   4
      ALIN=((CAPRB+RB)*TAN(THETA)-SQRT(RO*RO-RB*RB))/CAPRB          B   5
      ALFIN=SQRT(CAPRO*CAPRO-CAPRB*CAPRB)/CAPRB                     B   6
      RETURN                                                        B   7
      END                                                           B   8-
```

```
      SUBROUTINE ACCEL (RX,RY,RZ,GAMMA2,GAMMA3,GAMAPP,R1,R2,R3,R4,BETA3,
     1GX,GY,GZ,HX,HY,HZ,KX,KY,KZ,JX,JY,JZ,NX,NY,NZ,LX,LY,LZ,OX,OY,OZ,PX,
     2PY,PZ,QX,QY,QZ,T,OMX,OMY,OMZ,DOMX,DOMY,DOMZ,DDZ)
      COMMON /DATA/ RPM
      REAL KX,KY,KZ,JX,JY,JZ,NX,NY,NZ,LX,LY,LZ
      CALL AERO (RPM,T,OMX,OMY,OMZ,DOMX,DOMY,DOMZ,DDZ)
      GX=(OMY*RY+OMZ*RZ)*OMX-(OMY**2+OMZ**2)*RX+(DOMY*RZ-DOMZ*RY)
      GY=(OMX*RX+OMZ*RZ)*OMY-(OMX**2+OMZ**2)*RY+(DOMZ*RX-DOMX*RZ)
      GZ=(OMX*RX+OMY*RY)*OMZ-(OMX**2+OMY**2)*RZ+(DOMX*RY-DOMY*RX)+DDZ
      R4X=-R4*COS(GAMAPP+BETA3)
      R4Y=-R4*SIN(GAMAPP+BETA3)
      HX=OMY*OMX*R4Y-(OMY**2+OMZ**2)*R4X-DOMZ*R4Y
      HY=OMX*OMY*R4X-(OMX**2+OMZ**2)*R4Y+DOMZ*R4X
      HZ=(OMX*R4X+OMY*R4Y)*OMZ+(DOMX*R4Y-DOMY*R4X)
      KX=-(GX+HX)*COS(BETA3)-(GY+HY)*SIN(BETA3)
      KY=(GX+HX)*SIN(BETA3)-(GY+HY)*COS(BETA3)
      KZ=GZ+HZ
      R3X=R3*COS(GAMMA3)
      R3Y=R3*SIN(GAMMA3)
      JX=OMX*OMY*R3Y-(OMY**2+OMZ**2)*R3X-DOMZ*R3Y
      JY=OMX*OMY*R3X-(OMX**2+OMZ**2)*R3Y+DOMZ*R3X
      JZ=(OMX*R3X+OMY*R3Y)*OMZ+DOMX*R3Y-DOMY*R3X
      NX=GX+JX
      NY=GY+JY
      NZ=GZ+JZ
      LX=-(OMY**2+OMZ**2)*R1
      LY=(OMX*OMY+DOMZ)*R1
      LZ=(OMX*OMZ-DOMY)*R1
      OX=GX+LX
      OY=GY+LY
      OZ=GZ+LZ
      R2X=R2*COS(GAMMA2)
      R2Y=R2*SIN(GAMMA2)
      PX=OMX*OMY*R2Y-(OMY**2+OMZ**2)*R2X-DOMZ*R2Y
      PY=OMX*OMY*R2X-(OMX**2+OMZ**2)*R2Y+DOMZ*R2X
      PZ=(OMX*R2X+OMY*R2Y)*OMZ+DOMX*R2Y-DOMY*R2X
      QX=GX+PX
      QY=GY+PY
      QZ=GZ+PZ
      RETURN
      END
```

```
      SUBROUTINE IMPACT (PHI,DPHI,PSI,DPSI)
      COMMON A,B,C,R,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IE
     1ZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,RZ,
     2EREST,LAMBDA,DELTA,PHITOT,PHIPR,N31,N32,OMEGA,OM2,RC1,PHI1C,TEST1,
     3TEST2,NG1,NG2,NP2,NP3,CAPRB1,CAPRB2,RB2,RB3,THETA1,THETA2,R1,R2,R3
     4,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,GAMMA3,GAMA4P,GAMMA4,G
     5AMAPP,DELTA2,DELTA3,DELTA4,BETA1,BETA2,BETA3,D1,D2,AL1IN,AL1FIN,AL
     62IN,AL2FIN,ALPHA1,ALPHA2,IN,MU,MU1,RCP,PSIC,S1,S2,S4,S5,A1,A2,DPHI
     72,DPSI2,F23MAX,F12MAX,FF23MAX,FF12MAX,PNMAX,PN,ALPHEN,ALPHEX,LL,LU
     8,RHOF,RHOF1,RHOF2,RHOF3,S6
      REAL ISTOT,IZS,IZ2,IZZ1,IZZP,N31,N32
      ISTOT=IZS+IZ2*N32**2+IZZ1*N31**2
      G=(B*SIN(PHI)-C*SIN(PSI))/SIN(PSI+ALPHR)
      AONE=B*COS(PHI-PSI-ALPHR)
      DONE=C*COS(ALPHR)+G
      DPHIIN=DPHI
      DPSIIN=DPSI
      DPHI=(DPHIIN*(ISTOT*DONE**2-EREST*IZZP*AONE**2)+DPSIIN*IZZP*AONE*D
     1ONE*(1.+EREST))/(IZZP*AONE**2+ISTOT*DONE**2)
      DPSI=(DPHI*AONE-EREST*(DPSIIN*DONE-DPHIIN*AONE))/DONE
      PHID=PHI/ZZ
      PSID=PSI/ZZ
      IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 1
      WRITE (6,2)
      WRITE (6,3) PHID,DPHI,PSID,DPSI,PHITOT
    1 RETURN
C
C
C
    2 FORMAT (1H0,5X,6HIMPACT)
    3 FORMAT (1H0,18X,4HPHI=,F8.3,3X,7HPHIDOT=,F8.3,3X,4HPSI=,F8.3,3X,7H
     1PSIDOT=,F8.3,3X,7HPHITOT=,F8.3)
      END
```

```
      SUBROUTINE FCTF (T,X,DX)
      COMMON A,B,C,R,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IE
     1ZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,RZ,
     2EREST,LAMBDA,DELTA,PHITOT,PHIPR,N31,N32,OMEGA,OM2,RC1,PHI1C,TEST1,
     3TEST2,NG1,NG2,NP2,NP3,CAPRB1,CAPRB2,RB2,RB3,THETA1,THETA2,R1,R2,R3
     4,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,GAMMA3,GAMA4P,GAMMA4,G
     5AMAPP,DELTA2,DELTA3,DELTA4,BETA1,BETA2,BETA3,D1,D2,AL1IN,AL1FIN,AL
     62IN,AL2FIN,ALPHA1,ALPHA2,IN,MU,MU1,RCP,PSIC,S1,S2,S4,S5,A1,A2,DPHI
     72,DPSI2,F23MAX,F12MAX,FF23MAX,FF12MAX,PNMAX,PN,ALPHEN,ALPHEX,LL,LU
     8,RHOF,RHOF1,RHOF2,RHOF3,S6
      DIMENSION X(4), DX(4), PRMT(5)
      COMMON /DATA2/ KX,KY,OX,OY
      REAL M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,IXS,IYS,IZS,IXX1,IE
     1E1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,N31,N32,MU,MU1,KX,KY,KZ,LU,LL,J
     2X,JY,JZ,NX,NY,NZ,LX,LY,LZ,IPR,LAMBDA
      PHID=X(1)/ZZ
      DELPHI=PHID-PHIPR
      PHIT=(PHITOT+DELPHI)*ZZ
      IN=1
      IF (ALPHR.EQ.ALPHEN) S6=1.
      IF (ALPHR.EQ.ALPHEX) S6=-1.
      CALL AFIVE (T,X(1),X(2),X(3),X(4),0,0,0,0,0,0,DELPHI,0,IPR,AA29,AA
     130,AA31,AA48,AA49,AA50,AA100,AA101,AA102,AA104,AA105,AA106,AA107,A
     2A108,AA1C9,AA110,AA111,AA112,AA113,AA114,AA115,AA116,AA117,AA118,A
     3A119,AA120,AA51,AA32)
      BETA=X(3)+PSIC
      SB=SIN(BETA)
      CB=COS(BETA)
      DX(1)=X(2)
      DX(3)=X(4)
      DX(2)=(-AA118*X(2)**2-AA119*X(2)+AA120)/AA117
      DX(4)=(-AA32*X(4)**2-AA31*X(4)-AA116+MP*RCP*(KX*SB-KY*CB))/IPR
      RETURN
      END
```

```
      SUBROUTINE OUTPF (T,X,DX,IHLF,NDIM,PRMT)
      COMMON A,B,C,R,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IE
     1ZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,RZ,
     2EREST,LAMBDA,DELTA,PHITOT,PHIPR,N31,N32,OMEGA,OM2,RC1,PHI1C,TEST1,
     3TEST2,NG1,NG2,NP2,NP3,CAPRB1,CAPRB2,RB2,RB3,THETA1,THETA2,R1,R2,R3
     4,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,GAMMA3,GAMA4P,GAMMA4,G
     5AMAPP,DELTA2,DELTA3,DELTA4,BETA1,BETA2,BETA3,D1,D2,AL1IN,AL1FIN,AL
     62IN,AL2FIN,ALPHA1,ALPHA2,IN,MU,MU1,RCP,PSIC,S1,S2,S4,S5,A1,A2,DPHI
     72,DPSI2,F23MAX,F12MAX,FF23MAX,FF12MAX,PNMAX,PN,ALPHEN,ALPHEX,LL,LU
     8,RHOF,RHOF1,RHOF2,RHOF3,S6
      COMMON /ZETA/ PSI,TIME,G,DPSI,GP,PHICUTD
      COMMON /DATA2/ KX,KY,OX,OY
      DIMENSION X(4), DX(4), PRMT(5)
      REAL M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,IXS,IYS,IZS,IXX1,IE
     1E1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,N31,N32,MU,MU1,KX,KY,KZ,LU,LL,J
     2X,JY,JZ,NX,NY,NZ,LX,LY,LZ,IPR,LAMBDA
      PHID=X(1)/ZZ
      PSID=X(3)/ZZ
      DELPHI=PHID-PHIPR
      PHITOT=PHITOT+DELPHI
      PHIT=PHITOT*ZZ
      PHIPR=PHID
      IN=0
      IF (ALPHR.EQ.ALPHEN) S6=1.
      IF (ALPHR.EQ.ALPHEX) S6=-1.
      CALL AFIVE (T,X(1),X(2),X(3),X(4),0,0,0,0,0,0,0,DELPHI,0,IPR,AA29,AA
     130,AA31,AA48,AA49,AA50,AA100,AA101,AA102,AA104,AA105,AA106,AA107,A
     2A108,AA109,AA110,AA111,AA112,AA113,AA114,AA115,AA116,AA117,AA118,A
     3A119,AA120,AA51,AA32)
      PSI=X(3)
      DPSI=X(4)
      BETA=PSI+PSIC
      SB=SIN(BETA)
      CB=COS(BETA)
      DPSI2=(-AA32*X(4)**2-AA31*X(4)-AA116+MP*RCP*(KX*SB-KY*CB))/IPR
      DPHI2=(-AA118*X(2)**2-AA119*X(2)+AA120)/AA117
C
C     COMPUTATION OF CONTACT FORCE
C
      FF23=-(IZS*DPHI2+AA48*X(2)**2+AA50)/AA49
      FF12=(FF23*AA101+AA115+AA104*X(2)-AA100*DPHI2)/AA102
      IF (FF23.GT.FF23MAX) FF23MAX=FF23
      IF (FF12.GT.FF12MAX) FF12MAX=FF12
C
C     WRITE OUTPUT
C
      IF (PHITOT.GT.30.AND.PHITOT.LT.1450.) GO TO 1
      WRITE (6,6) T,PHID,X(2),PSID,X(4),PHITOT,FF12,FF23
    1 IF (T.EQ.TIME) GO TO 4
C
C     CHECK FOR CONTINUED FREE MOTION
C
      F=A*SIN(X(3)+ALPHR)-B*SIN(X(1)-X(3)-ALPHR)-C*SIN(ALPHR)
      GP=A*COS(X(3)+ALPHR)+B*COS(X(1)-X(3)-ALPHR)-C*COS(ALPHR)
      IF (PHID.LT.145..AND.F.GT.0) GO TO 2
      IF (PHID.GE.145..AND.F.LT.0) GO TO 3
      PRMT(5)=1.
```

```
    2 IF (GP.LT.O) PRMT(5)=1.
      GO TO 4
    3 IF (GP.GT.O) PRMT(5)=1.
    4 TIME=T
      IF (PHITOT.LT.PHICUTD) GO TO 5
      PRMT(5)=1.
    5 RETURN
C
C
C
    6 FORMAT (6X,3HT =,F8.5,3X,5HPHI =,F7.2,3X,8HPHIDOT =,F7.2,3X,5HPSI
     1=,F7.2,3X,8HPSIDOT =,F8.2,3X,8HPHITOT =,F7.2/20X,6HFF12 =,F7.3,3X,
     26HFF23 =,F7.3)
      END
```

```
      SUBROUTINE FCT (T,PHI,DPHI)
      COMMON A,B,C,R,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IE
     1ZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,RZ,
     2EREST,LAMBDA,DELTA,PHITOT,PHIPR,N31,N32,OMEGA,OM2,RC1,PHI1C,TEST1,
     3TEST2,NG1,NG2,NP2,NP3,CAPRB1,CAPRB2,RB2,RB3,THETA1,THETA2,R1,R2,R3
     4,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,GAMMA3,GAMA4P,GAMMA4,G
     5AMAPP,DELTA2,DELTA3,DELTA4,BETA1,BETA2,BETA3,D1,D2,AL1IN,AL1FIN,AL
     62IN,AL2FIN,ALPHA1,ALPHA2,IN,MU,MU1,RCP,PSIC,S1,S2,S4,S5,A1,A2,DPHI
     72,DPSI2,F23MAX,F12MAX,FF23MAX,FF12MAX,PNMAX,PN,ALPHEN,ALPHEX,LL,LU
     8,RHOF,RHOF1,RHOF2,RHOF3,S6
      DIMENSION PHI(2), DPHI(2)
      COMMON /DATA2/ KX,KY,OX,OY
      REAL M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,IXS,IYS,IZS,IXX1,IE
     1E1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,N31,N32,MU,MU1,KX,KY,KZ,LU,LL,J
     2X,JY,JZ,NX,NY,NZ,LX,LY,LZ,LAMBDA
      PHID=PHI(1)/ZZ
      DELPHI=PHID-PHIPR
      PHIT=(PHITOT+DELPHI)*ZZ
      IN=1
      IF (ALPHR.EQ.ALPHEN) S6=1.
      IF (ALPHR.EQ.ALPHEX) S6=-1.
      CALL KINEM (A,B,ALPHR,PHI,C,G,P,O,S,PSI,DPSI,AONE,BONE,CONE,DONE,U
     1,V,VST)
      CALL AFIVE (T,PHI(1),PHI(2),PSI,DPSI,AONE,BONE,CONE,DONE,U,V,DELPH
     1I,VST,IPR,AA29,AA30,AA31,AA48,AA49,AA50,AA100,AA101,AA102,AA104,AA
     2105,AA106,AA107,AA108,AA109,AA110,AA111,AA112,AA113,AA114,AA115,AA
     3116,AA117,AA118,AA119,AA120,AA51,AA32)
      BETA=PSI+PSIC
      SB=SIN(BETA)
      CB=COS(BETA)
      GAM=PHI1C+N31*PHITOT*ZZ
      SG=SIN(GAM)
      CG=COS(GAM)
      DPHI(1)=PHI(2)
      DPHI(2)=1./AA105*(-AA106*PHI(2)**2-AA107*PHI(2)+AA108+AA109*(OX*SG
     1-OY*CG)+AA110*(KX*SB-KY*CB))
      RETURN
      END
```

```
      SUBROUTINE OUTP (T,PHI,DPHI,IHLF,NDIM,PRMT)
      COMMON A,B,C,R,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IE
     1ZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,RZ,
     2EREST,LAMBDA,DELTA,PHITOT,PHIPR,N31,N32,OMEGA,OM2,RC1,PHI1C,TEST1,
     3TEST2,NG1,NG2,NP2,NP3,CAPRB1,CAPRB2,RB2,RB3,THETA1,THETA2,R1,R2,R3
     4,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,GAMMA3,GAMA4P,GAMMA4,G
     5AMAPP,DELTA2,DELTA3,DELTA4,BETA1,BETA2,BETA3,D1,D2,AL1IN,AL1FIN,AL
     62IN,AL2FIN,ALPHA1,ALPHA2,IN,MU,MU1,RCP,PSIC,S1,S2,S4,S5,A1,A2,DPHI
     72,DPSI2,F23MAX,F12MAX,FF23MAX,FF12MAX,PNMAX,PN,ALPHEN,ALPHEX,LL,LU
     8,RHOF,RHOF1,RHOF2,RHOF3,S6
      COMMON /ZETA/ PSI,TIME,G,DPSI,GP,PHICUTD
      COMMON /DATA2/ KX,KY,OX,OY
      DIMENSION PHI(2), DPHI(2), PRMT(5)
      REAL M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,IXS,IYS,IZS,IXX1,IE
     1E1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,N31,N32,MU,MU1,KX,KY,KZ,LU,LL,J
     2X,JY,JZ,NX,NY,NZ,LX,LY,LZ,LAMBDA,IPR
      PHID=PHI(1)/ZZ
      DELPHI=PHID-PHIPR
      PHIPR=PHID
      PHITOT=PHITOT+DELPHI
      PHIT=PHITOT*ZZ
      IN=0
      IF (ALPHR.EQ.ALPHEN) S6=1.
      IF (ALPHR.EQ.ALPHEX) S6=-1.
      CALL KINEM (A,B,ALPHR,PHI,C,G,P,Q,S,PSI,DPSI,AONE,BONE,CONE,DONE,U
     1,V,VST)
      CALL AFIVE (T,PHI(1),PHI(2),PSI,DPSI,AONE,BONE,CONE,DONE,U,V,DELPH
     1I,VST,IPR,AA29,AA30,AA31,AA48,AA49,AA50,AA100,AA101,AA102,AA104,AA
     2105,AA106,AA107,AA108,AA109,AA110,AA111,AA112,AA113,AA114,AA115,AA
     3116,AA117,AA118,AA119,AA120,AA51,AA32)
      BETA=PSI+PSIC
      SB=SIN(BETA)
      CB=COS(BETA)
      GAM=PHI1C+N31*PHITOT*ZZ
      CG=COS(GAM)
      SG=SIN(GAM)
      DPHI2=1./AA105*(-AA106*PHI(2)**2-AA107*PHI(2)+AA108+AA109*(OX*SG-O
     1Y*CG)+AA110*(KX*SB-KY*CB))
      DPSI2=U*DPHI2+V*PHI(2)**2
C
C     COMPUTATION OF CONTACT FORCES
C
      F23=(AA111*DPHI2+AA112*PHI(2)**2+AA113*PHI(2)+AA114)/AA101
      F12=(F23*AA101+AA115+AA104*PHI(2)-AA100*DPHI2)/AA102
      PN=(IZS*DPHI2+AA48*PHI(2)**2+F23*AA49+AA50)/AA51
      IF (F23.GT.F23MAX) F23MAX=F23
      IF (F12.GT.F12MAX) F12MAX=F12
      IF (PN.GT.PNMAX) PNMAX=PN
      PNPSI=(IPR*DPSI2+AA116+AA31*DPSI+AA32*DPSI**2-MP*RCP*(KX*SB-KY*CB)
     1)/AA29
C
C     TEST FOR CONTINUATION OF COUPLED MOTION
C
      IF (PHID.GT.150.) GO TO 1
      IF (.NOT.(G.GE.O.AND.PN.GT.O)) PRMT(5)=1.
      GO TO 2
    1 IF (.NOT.(G.LE.O.AND.PN.GT.O)) PRMT(5)=1.
```

```
C
C     WRITE OUTPUT
C
    2 IF (PHITOT.GT.30..AND.PHITOT.LT.1450.) GO TO 3
      PSID=PSI/ZZ
      WRITE (6,5) T,PHID,PHI(2),G,PSID,DPSI,PHITOT,F23,F12,PN,PNPSI,DPHI
     12
    3 IF (PHITOT.LT.PHICUTD) GO TO 4
      PRMT(5)=1.
    4 TIME=T
      RETURN
C
C
C
    5 FORMAT (6X,3HT =,F8.5,3X,5HPHI =,F7.2,3X,8HPHIDOT =,F7.2,3X,3HG =,
     1F6.4,3X,6HPSID =,F7.2,3X,8HPSIDOT =,F8.2,3X,8HPHITOT =,F7.2/20X,5H
     2F23 =,F7.4,3X,5HF12 =,F7.4,3X,4HPN =,F7.4,3X,7HPNPSI =,F7.4,3X,7HD
     3PHI2 =,E12.4)
      END
```

```
      SUBROUTINE AWON (S6,S7,ALPHR,BETA3,RCP,MP,IXXP,IEEP,IZZP,IXEP,IZXP
     1,IEZP,MU1,S4,S5,PSI,PSIC,OMX,OMY,OMZ,DOMX,DOMY,DOMZ,KX,KY,KZ,AA1,A
     2A2,AA3,AA4,AA5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,
     3AA17,AA18,AA19,AA20,AA21,AA22,AA23,PHITOT)
      REAL IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,KX,KY,KZ,MP,MU1
      BETA=PSI+PSIC
      ALPHAP=BETA+BETA3
      SA=SIN(ALPHAP)
      CA=COS(ALPHAP)
      SB=SIN(BETA)
      CB=COS(BETA)
      AA1=CB*(-IXXP*(DOMX*CA+DOMY*SA)+(IZZP-IEEP)*OMZ*(OMX*SA-OMY*CA)-IX
     1EP*(OMZ*(OMX*CA+OMY*SA)+(DOMX*SA-DOMY*CA))+IZXP*((OMX*CA+OMY*SA)*(
     2OMX*SA-OMY*CA)-DOMZ)-IEZP*((OMX*SA-OMY*CA)**2-OMZ**2))-SB*(IEEP*(D
     3OMX*SA-DOMY*CA)-(IXXP-IZZP)*OMZ*(OMX*CA+OMY*SA)-IEZP*((OMX*CA+OMY*
     4SA)*(OMX*SA-OMY*CA)+DOMZ)+IXEP*((DOMX*CA+DOMY*SA)-OMZ*(OMX*SA-OMY*
     5CA))-IZXP*(OMZ**2-(OMX*CA+OMY*SA)**2))
      AA2=(OMX*SA-OMY*CA)*((IXXP+IZZP-IEEP)*CB+2.*IXEP*SB)-(OMX*CA+OMY*S
     1A)*(2.*IXEP*CB+(IEEP-IXXP+IZZP)*SB)+2.*OMZ*(IEZP*CB+IZXP*SB)
      AA3=IEZP*CB+IZXP*SB
      AA4=IEZP*SB-IZXP*CB
      AA5=SB*(-IXXP*(DOMX*CA+DOMY*SA)+(IZZP-IEEP)*OMZ*(OMX*SA-OMY*CA)+IX
     1EP*(-OMZ*(OMX*CA+OMY*SA)-(DOMX*SA-DOMY*CA))-IZXP*(-(OMX*CA+OMY*SA)
     2*(OMX*SA-OMY*CA)+DOMZ)-IEZP*((OMX*SA-OMY*CA)**2-OMZ**2))+CB*(IEEP*
     3(DOMX*SA-DOMY*CA)-(IXXP-IZZP)*OMZ*(OMX*CA+OMY*SA)+IEZP*(-(OMX*CA+O
     4MY*SA)*(OMX*SA-OMY*CA)-DOMZ)-IXEP*(-(DOMX*CA+DOMY*SA)+OMZ*(OMX*SA-
     5OMY*CA))-IZXP*(OMZ**2-(OMX*CA+OMY*SA)**2))
      AA6=(OMX*SA-OMY*CA)*((IXXP+IZZP-IEEP)*SB-2.*IXEP*CB)+(OMX*CA+OMY*S
     1A)*((IEEP-IXXP+IZZP)*CB-2.*IXEP*SB)+2.*OMZ*(IEZP-IZXP)
      AA7=IEZP*SB-IZXP*CB
      AA8=-(IZXP*SB+IEZP*CB)
      AA9=IZZP*DOMZ-(IEEP-IXXP)*((OMX*CA+OMY*SA)*(OMX*SA-OMY*CA))+IZXP*(
     1OMZ*(OMX*SA-OMY*CA)+(DOMX*CA+DOMY*SA))-IEZP*((DOMX*SA-DOMY*CA)-OMZ
     2*(OMX*CA+OMY*SA))-IXEP*((OMX*CA+OMY*SA)**2-(OMX*SA-OMY*CA)**2)
      AA10=IZZP
      AA11=MU1*S5
      AA12=MP*RCP*(-OMX*OMX*SIN(BETA3)*SA-OMY*OMY*COS(BETA3)*CA+OMX*OMY*
     1SIN(ALPHAP+BETA3)-OMZ**2*CB-DOMZ*SB)+MP*KX
      AA13=-2.*OMZ*MP*RCP*CB
      AA14=-MP*RCP*CB
      AA15=-MP*RCP*SB
      AA16=-(MU1*S4*COS(PSI+ALPHR)-S7*SIN(PSI+ALPHR))
      AA17=MP*RCP*(-OMX**2*COS(BETA3)*SA+OMY**2*SIN(BETA3)*CA-OMX*OMY*CO
     1S(ALPHAP+BETA3)-OMZ**2*SB+DOMZ*CB)+MP*KY
      AA18=-2.*MP*RCP*OMZ*SB
      AA19=-MP*RCP*SB
      AA20=MP*RCP*CB
      AA21=-(COS(PSI+ALPHR)*S7+MU1*S4*SIN(PSI+ALPHR))
      AA22=ABS(MP*RCP*(-(DOMX+OMY*OMZ)*SA+(DOMY-OMX*OMZ)*CA)+MP*KZ)
      AA23=ABS(-2.*MP*RCP*(OMX*CA+OMY*SA))
      RETURN
      END
```

```
      SUBROUTINE CWON (LU,LL,MU1,S5,MP,RCP,PSI,PSIC,KX,KY,KZ,AA1,AA2,AA3
     1,AA4,AA5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,AA17,A
     2A18,AA19,AA20,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,C
     3C10,CC11,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20)
      REAL LU,LL,MP,MU1,KX,KY,KZ
      BETA=PSI+PSIC
      SB=SIN(BETA)
      CB=COS(BETA)
      CC1=ABS(-LL*AA12+MU1*S5*(AA1-LL*AA17)-AA5+MP*RCP*KZ*(MU1*S5*SB+CB)
     1)
      CC2=ABS(-LL*AA13+MU1*S5*(AA2-LL*AA18)-AA6)
      CC3=ABS(-LL*AA14+MU1*S5*(AA3-LL*AA19)-AA7)
      CC4=ABS(-LL*AA15+MU1*S5*(AA4-LL*AA20)-AA8)
      CC5=ABS(-LL*AA16-MU1*S5*LL*AA21)
      CC6=ABS(AA1-LL*AA17+MU1*S5*(LL*AA12+AA5)+MP*RCP*KZ*(SB-MU1*S5*CB))
      CC7=ABS(AA2-LL*AA18+MU1*S5*(AA6+LL*AA13))
      CC8=ABS(AA3-LL*AA19+MU1*S5*(AA7+LL*AA14))
      CC9=ABS(AA4-LL*AA20+MU1*S5*(LL*AA15-AA8))
      CC10=ABS(MU1*S5*LL*AA16-LL*AA21)
      CC11=ABS(LU*AA12-AA5+MU1*S5*(LU*AA17+AA1)+MP*RCP*KZ*(MU1*S5*SB+CB)
     1)
      CC12=ABS(LU*AA13-AA6+MU1*S5*(LU*AA18+AA2))
      CC13=ABS(LU*AA14-AA7+MU1*S5*(LU*AA19+AA3))
      CC14=ABS(LU*AA15-AA8+MU1*S5*(LU*AA20+AA4))
      CC15=ABS(LU*AA16+MU1*S5*LU*AA21)
      CC16=ABS(LU*AA17+AA1+MU1*S5*(AA5-LU*AA12)+MP*RCP*KZ*(SB-MU1*S5*CB)
     1)
      CC17=ABS(LU*AA18+AA2+MU1*S5*(AA6-LU*AA13))
      CC18=ABS(LU*AA19+AA3+MU1*S5*(AA7-LU*AA14))
      CC19=ABS(LU*AA20+AA4+MU1*S5*(AA8-LU*AA15))
      CC20=ABS(LU*AA21-MU1*S5*LU*AA16)
      RETURN
      END
```

```
      SUBROUTINE ATWO (S7,CONE,DONE,OMX,OMY,OMZ,DOMX,DOMY,DOMZ,DPSI,PSI,  K   1
     1NX,NY,NZ,AA16,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,C  K   2
     2C10,CC11,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20,AA24,AA25,AA  K   3
     326,AA27,AA28,AA29,AA30,AA31,AA32,AA33,AA34,AA35,AA36,AA37,AA38,AA3  K   4
     49,AA40,AA41,AA42,IPR)                                               K   5
      COMMON A,B,C,R,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IE  K   6
     1ZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,RZ,  K   7
     2EREST,LAMBDA,DELTA,PHITOT,PHIPR,N31,N32,OMEGA,OM2,RC1,PHI1C,TEST1,  K   8
     3TEST2,NG1,NG2,NP2,NP3,CAPRB1,CAPRB2,RB2,RB3,THETA1,THETA2,R1,R2,R3  K   9
     4,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,GAMMA3,GAMA4P,GAMMA4,G  K  10
     5AMAPP,DELTA2,DELTA3,DELTA4,BETA1,BETA2,BETA3,D1,D2,AL1IN,AL1FIN,AL  K  11
     62IN,AL2FIN,ALPHA1,ALPHA2,IN,MU,MU1,RCP,PSIC,S1,S2,S4,S5,A1,A2,DPHI  K  12
     72,DPSI2,F23MAX,F12MAX,FF23MAX,FF12MAX,PNMAX,PN,ALPHEN,ALPHEX,LL,LU  K  13
     8,RHOF,RHOF1,RHOF2,RHOF3,S6                                          K  14
      REAL LU,LL,LT,MU,MU1,IPR,IZZP,NX,NY,NZ,M3,IXS,IYS,IZS               K  15
      X=(LL+LU)*(1.+MU1**2)                                               K  16
      AA24=(CC1+CC6+CC11+CC16)/X                                          K  17
      AA25=(CC2+CC7+CC12+CC17)/X                                          K  18
      AA26=(CC3+CC8+CC13+CC18)/X                                          K  19
      AA27=(CC4+CC9+CC14+CC19)/X                                          K  20
      AA28=(CC5+CC10+CC15+CC20)/X                                         K  21
      AA29=S7*DONE-CONE*MU1*S4-MU1*RHOP*S5*AA28                           K  22
      AA30=MU1*S5*(RHOF*AA22+RHOP*AA24)                                   K  23
      AA31=MU1*(RHOF*AA23+RHOP*AA25)                                      K  24
      AA32=MU1*S5*RHOP*AA26                                               K  25
      AA333=MU1*RHOP*AA27                                                 K  26
      IF (DPSI*DPSI2.GE.0) IPR=IZZP+AA333                                 K  27
      IF (DPSI*DPSI2.LT.0) IPR=IZZP-AA333                                 K  28
      IF (IPR.LT.0) IPR=0                                                 K  29
      AA33=MU1*S4*COS(PSI+ALPHR+BETA3)-S7*SIN(PSI+ALPHR+BETA3)            K  30
      AA34=SIN(BETA2+THETA2)+MU*S2*COS(BETA2+THETA2)                      K  31
      AA35=-NX*M3                                                         K  32
      AA36=S7*COS(PSI+ALPHR+BETA3)+MU1*S4*SIN(PSI+ALPHR+BETA3)            K  33
      AA37=MU*S2*SIN(BETA2+THETA2)-COS(BETA2+THETA2)                      K  34
      AA38=-NY*M3                                                         K  35
      AA39=IXS*DOMX+OMY*OMZ*(IZS-IYS)                                     K  36
      AA40=IZS*OMY                                                        K  37
      AA41=IYS*DOMY+OMX*OMZ*(IXS-IZS)                                     K  38
      AA42=-IZS*OMX                                                       K  39
      RETURN                                                              K  40
      END                                                                 K  41-
```

```
      SUBROUTINE CTWO (LU,LL,MU,S6,AA33,AA34,AA35,AA36,AA37,AA38,AA39,AA
     140,AA41,AA42,CC21,CC22,CC23,CC24,CC25,CC26,CC27,CC28,CC29,CC30,CC3
     21,CC32,CC33,CC34,CC35,CC36)
      REAL LL,LU,MU
      CC21=ABS(LL*AA35-AA41+MU*(LL*AA38+AA39))
      CC22=ABS(LL*(AA33+MU*AA36))
      CC23=ABS(LL*(AA34+MU*AA37))
      CC24=ABS(MU*AA40-AA42)
      CC25=ABS(LL*AA38+AA39+MU*(AA41-LL*AA35))
      CC26=ABS(LL*(AA36-MU*AA33))
      CC27=ABS(LL*(AA37-MU*AA34))
      CC28=ABS(AA40+MU*AA42)
      CC29=ABS(MU*(AA39-LU*AA38)-LU*AA35-AA41)
      CC30=ABS(LU*(AA33+MU*AA36))
      CC31=ABS(LU*(AA34+MU*AA37))
      CC32=ABS(MU*AA40-AA42)
      CC33=ABS(MU*(AA41+LU*AA35)+AA39-LU*AA38)
      CC34=ABS(LU*(MU*AA33-AA36))
      CC35=ABS(LU*(MU*AA34-AA37))
      CC36=ABS(AA40+MU*AA42)
      RETURN
      END
```

```
      SUBROUTINE ATHREE (S7,DPHI,AONE,BONE,OMX,OMY,OMZ,DOMX,DOMY,DOMZ,NZ
     1,OX,OY,OZ,CC21,CC22,CC23,CC24,CC25,CC26,CC27,CC28,CC29,CC30,CC31,C
     2C32,CC33,CC34,CC35,CC36,AA43,AA44,AA45,AA46,AA47,AA48,AA49,AA50,AA
     351,AA52,AA53,AA54,AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA6
     44,AA65,AA66,AA67,AA68,AA69,AA70,AA71)
      COMMON A,B,C,R,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IE
     1ZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,RZ,
     2EREST,LAMBDA,DELTA,PHITOT,PHIPR,N31,N32,OMEGA,OM2,RC1,PHI1C,TEST1,
     3TEST2,NG1,NG2,NP2,NP3,CAPRB1,CAPRB2,RB2,RB3,THETA1,THETA2,R1,R2,R3
     4,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,GAMMA3,GAMA4P,GAMMA4,G
     5AMAPP,DELTA2,DELTA3,DELTA4,BETA1,BETA2,BETA3,D1,D2,AL1IN,AL1FIN,AL
     62IN,AL2FIN,ALPHA1,ALPHA2,IN,MU,MU1,RCP,PSIC,S1,S2,S4,S5,A1,A2,DPHI
     72,DPSI2,F23MAX,F12MAX,FF23MAX,FF12MAX,PNMAX,PN,ALPHEN,ALPHEX,LL,LU
     8,RHOF,RHOF1,RHOF2,RHOF3,S6
      REAL LU,LL,MU,M3,NX,NY,NZ,IZS,MU1,N31,IXX1,IZZ1,IEE1,IXE1,IZX1,IEZ
     11,M1,M2
      XX=(LU+LL)*(1.+MU**2)
      AA43=(CC21+CC25+CC29+CC33)/XX
      AA44=(CC22+CC26+CC30+CC34)/XX
      AA45=(CC23+CC27+CC31+CC35)/XX
      AA46=(CC24+CC28+CC32+CC36)/XX
      AA47=ABS(NZ*M3)
      IF (DPHI.EQ.O) GO TO 1
      AA48=MU*RHO3*AA46/ABS(DPHI)
      GO TO 2
    1 AA48=O
    2 AA49=MU*(S2*(D2-A2)+RHO3*AA45)-RB3
      AA50=IZS*DOMZ+MU*(RHOF3*AA47+RHO3*AA43)
      AA51=-S7*AONE+BONE*MU1*S4-MU*RHO3*AA44
      GAM=PHI1C+N31*PHITOT*ZZ
      CG=COS(GAM)
      SG=SIN(GAM)
      AA52=CG*(IXX1*(DOMX*CG+DOMY*SG)+(IZZ1-IEE1)*OMZ*(-OMX*SG+OMY*CG)+I
     1XE1*(OMZ*(OMX*CG+OMY*SG)+(DOMX*SG-DOMY*CG))-IZX1*((OMX*CG+OMY*SG)*
     2(-OMX*SG+OMY*CG)+DOMZ)-IEZ1*((-OMX*SG+OMY*CG)**2-OMZ**2))-SG*(IEE1
     3*(-DOMX*SG+DOMY*CG)+(IXX1-IZZ1)*OMZ*(OMX*CG+OMY*SG)+IEZ1*((OMX*CG+
     4OMY*SG)*(-OMX*SG+OMY*CG)-DOMZ)-IXE1*((DOMX*CG+DOMY*SG)+OMZ*(-OMX*S
     5G+OMY*CG))-IZX1*(OMZ**2-(OMX*CG+OMY*SG)**2))
      AA53=N31*((-OMX*SG+OMY*CG)*((IXX1+IZZ1-IEE1)*CG+2.*IXE1*SG)+(OMX*C
     1G+OMY*SG)*((IEE1-IXX1+IZZ1)*SG+2.*IXE1*CG)+2.*OMZ*(IXE1*CG+IZX1*SG
     2))
      AA54=N31**2*(IXE1*CG+IZX1*SG)
      AA55=N31*(-IZX1*CG+IEZ1*SG)
      AA56=SG*(IXX1*(DOMX*CG+DOMY*SG)+(IZZ1-IEE1)*(-OMX*SG+OMY*CG)*OMZ+I
     1XE1*(OMZ*(OMX*CG+OMY*SG)-(-DOMX*SG+DOMY*CG))-IZX1*((OMX*CG+OMY*SG)
     2*(-OMX*SG+OMY*CG)+DOMZ)-IEZ1*((-OMX*SG+OMY*CG)**2-OMZ**2))+CG*(IEE
     31*(-DOMX*SG+DOMY*CG)+(IXX1-IZZ1)*(OMX*CG+OMY*SG)*OMZ+IEZ1*((OMX*CG
     4+OMY*SG)*(-OMX*SG+OMY*CG)-DOMZ)-IXE1*(DOMX*CG+DOMY*SG+OMZ*(-OMX*SG
     5+OMY*CG))-IZX1*(OMZ**2-(OMX*CG+OMY*SG)**2))
      AA57=N31*((-OMX*SG+OMY*CG)*((IXX1+IZZ1-IEE1)*SG-2.*IXE1*CG)+(OMX*C
     1G+OMY*SG)*(2.*IXE1*SG+(IXX1-IZZ1-IEE1)*CG)+2.*OMZ*(IEZ1*SG-IZX1*CG
     2))
      AA58=N31**2*(IEZ1*SG-IZX1*CG)
      AA59=-N31*(IZX1*SG+IEZ1*CG)
      AA60=IZZ1*DOMZ+(IEE1-IXX1)*(OMX*CG+OMY*SG)*(-OMX*SG+OMY*CG)+IZX1*(
     1(-OMX*SG+OMY*CG)*OMZ-DOMX*CG-DOMY*SG)+IEZ1*(DOMX*SG-DOMY*CG-OMZ*(O
     2MX*CG+OMY*SG))-IXE1*((OMX*CG+OMY*SG)**2-(-OMX*SG+OMY*CG)**2)
```

```
      AA61=N31*IZZ1
      AA62=M1*RC1*(-OMY**2*CG+OMX*OMY*SG-OMZ**2*CG-DOMZ*SG)+M1*OX
      AA63=-2.*M1*RC1*OMZ*N31*CG
      AA64=-M1*RC1*N31**2*CG
      AA65=-M1*RC1*N31*SG
      AA66=MU*S1*COS(BETA1-THETA1)-SIN(BETA1-THETA1)
      AA67=M1*RC1*(-OMX**2*SG+OMX*OMY*CG-OMZ**2*SG+DOMZ*CG)+M1*OY
      AA68=-2.*M1*RC1*N31*OMZ*SG
      AA69=-M1*RC1*N31**2*SG
      AA70=-M1*RC1*N31*CG
      AA71=COS(BETA1-THETA1)+MU*S1*SIN(BETA1-THETA1)
      RETURN
      END
```

```
      SUBROUTINE CTHREE (LU,LL,PHI1C,PHITOT,N31,M1,RC1,MU,OX,OY,OZ,AA52,
     1AA53,AA54,AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA64,AA65,A
     2A66,AA67,AA68,AA69,AA70,AA71,CC37,CC38,CC39,CC40,CC41,CC42,CC43,CC
     344,CC45,CC46,CC47,CC48,CC49,CC50,CC51,CC52,CC53,CC54,CC55,CC56)
      REAL LU,LL,N31,M1,MU
      ZZ=3.14159/180.
      GAM=PHI1C+N31*PHITOT*ZZ
      CG=COS(GAM)
      SG=SIN(GAM)
      CC37=ABS(-LL*AA62+MU*(AA52-LL*AA67)-AA56+M1*RC1*OZ*(MU*SG+CG))
      CC38=ABS(-LL*AA63+MU*(AA53-LL*AA68)-AA57)
      CC39=ABS(-LL*AA64+MU*(AA54-LL*AA69)-AA58)
      CC40=ABS(-LL*AA65+MU*(AA55-LL*AA70)-AA59)
      CC41=ABS(-LL*(AA66+MU*AA71))
      CC42=ABS(-LL*AA67+MU*(AA56+LL*AA62)+AA52+M1*RC1*OZ*(SG-MU*CG))
      CC43=ABS(-LL*AA68+MU*(LL*AA63+AA57)+AA53)
      CC44=ABS(-LL*AA69+MU*(LL*AA64+AA58)+AA54)
      CC45=ABS(-LL*AA70+MU*(LL*AA65+AA59)+AA55)
      CC46=ABS(LL*(MU*AA66-AA71))
      CC47=ABS(LU*AA62+MU*(LU*AA67+AA52)-AA56+M1*RC1*OZ*(MU*SG+CG))
      CC48=ABS(LU*AA63+MU*(LU*AA68+AA53)-AA57)
      CC49=ABS(LU*AA64+MU*(LU*AA69+AA54)-AA58)
      CC50=ABS(LU*AA65+MU*(LU*AA70+AA55)-AA59)
      CC51=ABS(LU*(AA66+MU*AA71))
      CC52=ABS(LU*AA67+MU*(AA56-LU*AA62)+AA52+M1*RC1*OZ*(SG-MU*CG))
      CC53=ABS(LU*AA68+MU*(AA57-LU*AA63)+AA53)
      CC54=ABS(LU*AA69+MU*(AA58-LU*AA64)+AA54)
      CC55=ABS(LU*AA70+MU*(AA59-LU*AA65)+AA55)
      CC56=ABS(LU*(AA71-MU*AA66))
      RETURN
      END
```

```
      SUBROUTINE AFOUR (PHI,DPHI,OMX,OMY,OMZ,DOMX,DOMY,DOMZ,OX,OY,OZ,QX,
     1QY,QZ,CC37,CC38,CC39,CC40,CC41,CC42,CC43,CC44,CC45,CC46,CC47,CC48,
     2CC49,CC50,CC51,CC52,CC53,CC54,CC55,CC56,AA61,AA72,AA73,AA74,AA75,A
     3A76,AA77,AA78,AA79,AA80,AA81,AA82,AA83,AA84,AA85,AA86,AA87,AA88,AA
     489,AA90,AA91,AA92,AA93,I1R)
      REAL M1,M2,LU,LL,I1R,IX2,IY2,IZ2,MU,N31,N32
      COMMON A,B,C,R,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IE
     1ZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,RZ,
     2EREST,LAMBDA,DELTA,PHITOT,PHIPR,N31,N32,OMEGA,OM2,RC1,PHI1C,TEST1,
     3TEST2,NG1,NG2,NP2,NP3,CAPRB1,CAPRB2,RB2,RB3,THETA1,THETA2,R1,R2,R3
     4,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,GAMMA3,GAMA4P,GAMMA4,G
     5AMAPP,DELTA2,DELTA3,DELTA4,BETA1,BETA2,BETA3,D1,D2,AL1IN,AL1FIN,AL
     62IN,AL2FIN,ALPHA1,ALPHA2,IN,MU,MU1,RCP,PSIC,S1,S2,S4,S5,A1,A2,DPHI
     72,DPSI2,F23MAX,F12MAX,FF23MAX,FF12MAX,PNMAX,PN,ALPHEN,ALPHEX,LL,LU
     8,RHOF,RHOF1,RHOF2,RHOF3,S6
      GAM=PHI1C+N31*PHITOT*ZZ
      CG=COS(GAM)
      SG=SIN(GAM)
      XX=(LU+LL)*(1.+MU**2)
      AA72=ABS(M1*RC1*(OMZ*(OMX*CG+OMY*SG)+DOMX*SG-DOMY*CG)+M1*OZ)
      AA73=ABS(2.*M1*RC1*N31*(OMX*CG+OMY*SG))
      AA74=(CC37+CC42+CC47+CC52)/XX
      AA75=(CC38+CC43+CC48+CC53)/XX
      AA76=(CC39+CC44+CC49+CC54)/XX
      AA77=(CC40+CC45+CC50+CC55)/XX
      AA78=(CC41+CC46+CC51+CC56)/XX
      AA79=CAPRB1-MU*S1*A1+MU*RHO1*AA78
      AA80=MU*(RHOF1*AA72+RHO1*AA74)
      AA81=ABS(MU)*(RHOF1*AA73+RHO1*AA75)
      AA82=MU*RHO1*AA76
      AA83=ABS(MU)*RHO1*AA77
      IF (DPHI*DPHI2.GE.0) I1R=AA61+AA83
      IF (DPHI*DPHI2.LT.0) I1R=AA61-AA83
      IF (I1R.LT.0) I1R=0
      AA84=-(SIN(BETA2+THETA2)+MU*S2*COS(BETA2+THETA2))
      AA85=-(SIN(BETA1-THETA1)-MU*S1*COS(BETA1-THETA1))
      AA86=-M2*QX
      AA87=-(MU*S2*SIN(BETA2+THETA2)-COS(BETA2+THETA2))
      AA88=MU*S1*SIN(BETA1-THETA1)+COS(BETA1-THETA1)
      AA89=-M2*QY
      AA90=-(IX2*DOMX+OMY*OMZ*(IZ2-IY2))
      AA91=-IZ2*N32*OMY
      AA92=-(IY2*DOMY+OMX*OMZ*(IX2-IZ2))
      AA93=IZ2*OMX*N32
      RETURN
      END
```

```
      SUBROUTINE CFOUR (LU,LL,MU,AA84,AA85,AA86,AA87,AA88,AA89,AA90,AA91
     1,AA92,AA93,CC57,CC58,CC59,CC60,CC61,CC62,CC63,CC64,CC65,CC66,CC67,
     2CC68,CC69,CC70,CC71,CC72)
      REAL MU,LL,LU
      CC57=ABS(-LL*AA86+MU*(LL*AA89-AA90)-AA92)
      CC58=ABS(MU*AA91+AA93)
      CC59=ABS(LL*(MU*AA87-AA84))
      CC60=ABS(LL*(MU*AA88-AA85))
      CC61=ABS(-LL*AA89-MU*(LL*AA86+AA92)+AA90)
      CC62=ABS(AA91-MU*AA93)
      CC63=ABS(LL*(MU*AA84+AA87))
      CC64=ABS(LL*(MU*AA85+AA88))
      CC65=ABS(-MU*(LU*AA89+AA90)+LU*AA86-AA92)
      CC66=ABS(MU*AA91+AA93)
      CC67=ABS(LU*(AA84-MU*AA87))
      CC68=ABS(LU*(AA85-MU*AA88))
      CC69=ABS(LU*AA89+MU*(LU*AA86-AA92)+AA90)
      CC70=ABS(AA91-MU*AA93)
      CC71=ABS(LU*(MU*AA84+AA87))
      CC72=ABS(LU*(MU*AA85+AA88))
      RETURN
      END
```

```
      SUBROUTINE AFIVE (T,PHI,DPHI,PSI,DPSI,AONE,BONE,CONE,DONE,U,V,DELP
     1HI,VST,IPR,AA29,AA30,AA31,AA48,AA49,AA50,AA100,AA101,AA102,AA104,A
     2A105,AA106,AA107,AA108,AA109,AA110,AA111,AA112,AA113,AA114,AA115,A
     3A116,AA117,AA118,AA119,AA120,AA51,AA32)
      REAL M1,M2,M3,MP,IXXU,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,IXS,IYS
     1,IZS,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,N31,N32,MU,MU1,KX,KY,KZ,JX,JY,J
     2Z,LX,LY,LZ,NX,NY,NZ,LU,LL,LAMBDA,NG1,NG2,NP2,NP3,IPR,I1R
      COMMCN A,B,C,R,ALPHR,PI,ZZ,M1,M2,M3,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IE
     1ZP,IXS,IYS,IZS,IXX1,IEE1,IZZ1,IXE1,IZX1,IEZ1,IX2,IY2,IZ2,RX,RY,RZ,
     2EREST,LAMBDA,DELTA,PHITOT,PHIPR,N31,N32,OMEGA,OM2,RC1,PHI1C,TEST1,
     3TEST2,NG1,NG2,NP2,NP3,CAPRB1,CAPRB2,RB2,RB3,THETA1,THETA2,R1,R2,R3
     4,R4,RHO1,RHO2,RHO3,RHOP,J1,J2,GAMMA2,GAMA3P,GAMMA3,GAMA4P,GAMMA4,G
     5AMAPP,DELTA2,DELTA3,DELTA4,BETA1,BETA2,BETA3,D1,D2,AL1IN,AL1FIN,AL
     62IN,AL2FIN,ALPHA1,ALPHA2,IN,MU,MU1,RCP,PSIC,S1,S2,S4,S5,A1,A2,DPHI
     72,DPSI2,F23MAX,F12MAX,FF23MAX,FF12MAX,PNMAX,PN,ALPHEN,ALPHEX,LL,LU
     8,RHOF,RHOF1,RHOF2,RHOF3,S6
      COMMON /DATA2/ KX,KY,OX,OY
      CALL ACCEL (RX,RY,RZ,GAMMA2,GAMMA3,GAMAPP,R1,R2,R3,R4,BETA3,GX,GY,
     1GZ,HX,HY,HZ,KX,KY,KZ,JX,JY,JZ,NX,NY,NZ,LX,LY,LZ,OX,OY,OZ,PX,PY,PZ,
     2QX,QY,QZ,T,OMX,OMY,OMZ,DOMX,DOMY,DOMZ,DDZ)
      IF (DPHI.EQ.O) GO TO 1
      MU=ABS(MU)*DPHI/ABS(DPHI)
    1 IF (IN.EQ.O) GO TO 2
C
C     UPDATE VALUES OF ALPHAS
C
      DELAL2=DELPHI*ZZ
      DELAL1=DELAL2*RB2/CAPRB1
      ALPHA1=ALPHA1+DELAL1
      ALPHA2=ALPHA2+DELAL2
      IF (ALPHA1.GT.AL1FIN) ALPHA1=AL1IN
      IF (ALPHA2.GT.AL2FIN) ALPHA2=AL2IN
C
C     DETERMINATION OF SIGNUMS
C
    2 IF (ALPHA1.LT.TEST1) S1=1.
      IF (ALPHA2.LT.TEST2) S2=1.
      IF (ALPHA1.EQ.TEST1) S1=O
      IF (ALPHA2.EQ.TEST2) S2=O
      IF (ALPHA1.GT.TEST1) S1=-1.
      IF (ALPHA2.GT.TEST2) S2=-1.
      IF (VST.NE.O) GO TO 3
      S4=1.
      GO TO 4
    3 S4=VST/ABS(VST)
    4 IF (DPSI.NE.O) GO TO 5
      S5=1.
      GO TO 6
    5 S5=DPSI/ABS(DPSI)
C
C     COMPUTATION OF A1 AND A2
C
    6 A1=ALPHA1*CAPRB1
      A2=ALPHA2*CAPRB2
      IF (ALPHR.EQ.ALPHEN) S7=1.
      IF (ALPHR.EQ.ALPHEX) S7=-1.
      CALL AWON (S6,S7,ALPHR,BETA3,RCP,MP,IXXP,IEEP,IZZP,IXEP,IZXP,IEZP,
```

```
     1MU1,S4,S5,PSI,PSIC,OMX,OMY,OMZ,DOMX,DOMY,DOMZ,KX,KY,KZ,AA1,AA2,AA3
     2,AA4,AA5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,AA17,A
     3A18,AA19,AA20,AA21,AA22,AA23,PHITOT)
      CALL CWON (LU,LL,MU1,S5,MP,RCP,PSI,PSIC,KX,KY,KZ,AA1,AA2,AA3,AA4,A
     1A5,AA6,AA7,AA8,AA9,AA10,AA11,AA12,AA13,AA14,AA15,AA16,AA17,AA18,AA
     219,AA20,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,CC10,CC
     311,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20)
      CALL ATWO (S7,CONE,DONE,OMX,OMY,OMZ,DOMX,DOMY,DOMZ,DPSI,PSI,NX,NY,
     1NZ,AA16,AA21,AA22,AA23,CC1,CC2,CC3,CC4,CC5,CC6,CC7,CC8,CC9,CC10,CC
     211,CC12,CC13,CC14,CC15,CC16,CC17,CC18,CC19,CC20,AA24,AA25,AA26,AA2
     37,AA28,AA29,AA30,AA31,AA32,AA33,AA34,AA35,AA36,AA37,AA38,AA39,AA40
     4,AA41,AA42,IPR)
      CALL CTWO (LU,LL,MU,S6,AA33,AA34,AA35,AA36,AA37,AA38,AA39,AA40,AA4
     11,AA42,CC21,CC22,CC23,CC24,CC25,CC26,CC27,CC28,CC29,CC30,CC31,CC32
     2,CC33,CC34,CC35,CC36)
      CALL ATHREE (S7,DPHI,AONE,BONE,OMX,OMY,OMZ,DOMX,DOMY,DOMZ,NZ,OX,OY
     1,OZ,CC21,CC22,CC23,CC24,CC25,CC26,CC27,CC28,CC29,CC30,CC31,CC32,CC
     233,CC34,CC35,CC36,AA43,AA44,AA45,AA46,AA47,AA48,AA49,AA50,AA51,AA5
     32,AA53,AA54,AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA64,AA65
     4,AA66,AA67,AA68,AA69,AA70,AA71)
      CALL CTHREE (LU,LL,PHI1C,PHITOT,N31,M1,RC1,MU,OX,OY,OZ,AA52,AA53,A
     1A54,AA55,AA56,AA57,AA58,AA59,AA60,AA61,AA62,AA63,AA64,AA65,AA66,AA
     267,AA68,AA69,AA70,AA71,CC37,CC38,CC39,CC40,CC41,CC42,CC43,CC44,CC4
     35,CC46,CC47,CC48,CC49,CC50,CC51,CC52,CC53,CC54,CC55,CC56)
      CALL AFOUR (PHI,DPHI,OMX,OMY,OMZ,DOMX,DOMY,DOMZ,OX,OY,OZ,OX,QY,OZ,
     1CC37,CC38,CC39,CC40,CC41,CC42,CC43,CC44,CC45,CC46,CC47,CC48,CC49,C
     2C50,CC51,CC52,CC53,CC54,CC55,CC56,AA61,AA72,AA73,AA74,AA75,AA76,AA
     377,AA78,AA79,AA80,AA81,AA82,AA83,AA84,AA85,AA86,AA87,AA88,AA89,AA9
     40,AA91,AA92,AA93,I1R)
      CALL CFOUR (LU,LL,MU,AA84,AA85,AA86,AA87,AA88,AA89,AA90,AA91,AA92,
     1AA93,CC57,CC58,CC59,CC60,CC61,CC62,CC63,CC64,CC65,CC66,CC67,CC68,C
     2C69,CC70,CC71,CC72)
      XX=(LU+LL)*(1.+MU**2)
      GAM=PHI1C+N31 PHITOT*ZZ
      SG=SIN(GAM)
      CG=COS(GAM)
      AA94=(CC57+CC61+CC65+CC69)/XX
      AA95=(CC58+CC62+CC66+CC70)/XX
      AA95=(CC59+CC63+CC67+CC71)/XX
      AA97=(CC60+CC64+CC68+CC72)/XX
      AA98=ABS(M2*QZ)
      AA99=IZ2*DOMZ
      AA100=IZ2*N32
      AA101=CAPRB2-MU*S2*A2+MU*RHO2*AA96
      AA102=RB2-MU*S1*(D1-A1)-MU*RHO2*AA97
      AA103=MU*(RHOF2*AA98+RHO2*AA94)
      AA104=ABS(MU)*RHO2*AA95
      AA105=AA51*IPR*U-AA29*IZS-(AA29*AA49*AA100)/AA101+(AA29*AA49*AA102
     1*I1R)/(AA101*AA79)
      AA106=AA51*(AA32*U*U+IPR*V)-AA29*AA48+(AA29*AA49*AA102*AA82)/(AA10
     11*AA79)
      AA107=AA51*AA31*U+(AA29*AA49)/AA101*((AA102*AA81)/AA79+AA[illegible]
      AA108=-(AA29*AA49)/AA101*(AA102*(AA80+AA60)/AA79+AA103-A[illegible]+AA29
     1AA50-AA51*(AA9+AA30)
      AA109=AA29*AA49*AA102*M1*RC1/(AA101*AA79)
      AA110=AA51*MP*RCP
      AA111=-AA102*I1R/AA79 AA100
```

```
      AA112=-AA102*AA82/AA79
      AA113=-(AA102*AA81/AA79+AA104)
      AA114=-(AA80+AA60)*AA102/AA79-AA103+AA99+AA102*M1*RC1*(OX*SG-OY*CG
     1)/AA79
      AA115=AA103-AA99
      AA116=AA9+AA30
      AA117=IZS+AA49*AA111/AA101
      AA118=AA48+AA49*AA112/AA101
      AA119=AA49*AA113/AA101
      AA120=-(AA50+AA49*AA114/AA101)
      RETURN
      END
```

```
      SUBROUTINE AERO (RPM,T,OMX,OMY,OMZ,DOMX,DOMY,DOMZ,DDZ)
      REAL KP,KN
      KP=100.
      KN=10.
      PI=3.14159
      Z=PI/180.
      THETIN=8.*Z
      DPHIE=RPM*2.*PI/60.
      PHIE=DPHIE*T
      DPSIE=DPHIE/KP
      PSIE=DPSIE*T
      TV=2.*Z
      THET=THETIN+TV*SIN(KN*DPSIE*T)
      DTHET=TV*KN*DPSIE*COS(KN*DPSIE*T)
      DDZ=-386.*10.
      DTHET2=-TV*KN**2*DPSIE**2*SIN(KN*DPSIE*T)
      OMX=DTHET*COS(PHIE)+DPSIE*SIN(THET)*SIN(PHIE)
      OMY=-DTHET*SIN(PHIE)+DPSIE*SIN(THET)*COS(PHIE)
      OMZ=DPHIE+DPSIE*COS(THET)
      DOMX=DTHET2*COS(PHIE)-DTHET*DPHIE*SIN(PHIE)+DPSIE*DTHET*COS(THET)*
     1SIN(PHIE)+DPSIE*DPHIE*SIN(THET)*COS(PHIE)
      DOMY=-DTHET2*SIN(PHIE)-DTHET*DPHIE*COS(PHIE)+DPSIE*DTHET*COS(THET)
     1*COS(PHIE)-DPSIE*DPHIE*SIN(THET)*SIN(PHIE)
      DOMZ=-DPSIE*DTHET*SIN(THET)
      RETURN
      END
```

```
      SUBROUTINE KINEM (A:B,ALPHR,PHI,C,G,P,Q,S,PSI,DPSI,AONE,BONE,CONE,  S   1
     1DONE,U,V,VST)                                                         S   2
      DIMENSION PHI(2)                                                      S   3
      PI=3.14159                                                            S   4
      CAPA=A*COS(ALPHR)+B*COS(PHI(1)-ALPHR)                                 S   5
      CAPB=A*SIN(ALPHR)-B*SIN(PHI(1)-ALPHR)                                 S   6
      CAPC=C*SIN(ALPHR)                                                     S   7
      PSI=2.*ATAN2((CAPA-SQRT(CAPA**2+CAPB**2-CAPC**2)),(CAPB+CAPC))        S   8
      IF (PSI.LT.O.) PSI=2.*PI+PSI                                          S   9
      G=(B*SIN(PHI(1))-C*SIN(PSI))/SIN(PSI+ALPHR)                           S  10
      P=B*COS(PHI(1)-ALPHR-PSI)                                             S  11
      Q=A*COS(PSI+ALPHR)+B*COS(PHI(1)-ALPHR-PSI)                            S  12
      U=P/Q                                                                 S  13
      V=1./Q**3*(A*P**2*SIN(PSI+ALPHR)-B*(P-Q)**2*SIN(PHI(1)-ALPHR-PSI))    S  14
      AONE=B*COS(PHI(1)-PSI-ALPHR)                                          S  15
      BONE=B*SIN(PHI(1)-PSI-ALPHR)                                          S  16
      CONE=-C*SIN(ALPHR)                                                    S  17
      DONE=C*COS(ALPHR)+G                                                   S  18
      DPSI=U*PHI(2)                                                         S  19
      VST=-PHI(2)*B*SIN(PHI(1)-PSI-ALPHR)-DPSI*C*SIN(ALPHR)                 S  20
      RETURN                                                                S  21
      END                                                                   S  22-
```

```
T =  .00003   PHI = 139.03   PHIDOT =  36.62   G = .0221   PSID =  42.11   PSIDOT =  31.26   PHITOT =   .03
              F23 = 2.5459   F12 = 9.8528   PN =  .3391   PNPSI =  .3391   DPHI2 =  .1212E+07
T =  .00004   PHI = 139.04   PHIDOT =  42.68   G = .0221   PSID =  42.12   PSIDOT =  36.45   PHITOT =   .04
              F23 = 2.5472   F12 = 9.8522   PN =  .3400   PNPSI =  .3400   DPHI2 =  .1215E+07
T =  .00004   PHI = 139.06   PHIDOT =  48.75   G = .0220   PSID =  42.13   PSIDOT =  41.64   PHITOT =   .06
              F23 = 2.5472   F12 = 9.8520   PN =  .3402   PNPSI =  .3402   DPHI2 =  .1214E+07
T =  .00005   PHI = 139.07   PHIDOT =  54.82   G = .0220   PSID =  42.14   PSIDOT =  46.85   PHITOT =   .07
              F23 = 2.5490   F12 = 9.8513   PN =  .3413   PNPSI =  .3413   DPHI2 =  .1218E+07
T =  .00005   PHI = 139.09   PHIDOT =  60.90   G = .0219   PSID =  42.16   PSIDOT =  52.07   PHITOT =   .09
              F23 = 2.5490   F12 = 9.8511   PN =  .3416   PNPSI =  .3416   DPHI2 =  .1217E+07
T =  .00005   PHI = 139.11   PHIDOT =  66.99   G = .0218   PSID =  42.17   PSIDOT =  57.31   PHITOT =   .11
              F23 = 2.5512   F12 = 9.8504   PN =  .3430   PNPSI =  .3430   DPHI2 =  .1222E+07
T =  .00006   PHI = 139.13   PHIDOT =  73.09   G = .0218   PSID =  42.19   PSIDOT =  62.56   PHITOT =   .13
              F23 = 2.5513   F12 = 9.8503   PN =  .3433   PNPSI =  .3433   DPHI2 =  .1220E+07
T =  .00006   PHI = 139.15   PHIDOT =  79.19   G = .0217   PSID =  42.21   PSIDOT =  67.83   PHITOT =   .15
              F23 = 2.5539   F12 = 9.8495   PN =  .3450   PNPSI =  .3450   DPHI2 =  .1227E+07
T =  .00007   PHI = 139.17   PHIDOT =  85.31   G = .0216   PSID =  42.23   PSIDOT =  73.12   PHITOT =   .17
              F23 = 2.5540   F12 = 9.8494   PN =  .3454   PNPSI =  .3454   DPHI2 =  .1225E+07
T =  .00007   PHI = 139.20   PHIDOT =  91.44   G = .0215   PSID =  42.25   PSIDOT =  78.43   PHITOT =   .20
              F23 = 2.5571   F12 = 9.8487   PN =  .3473   PNPSI =  .3473   DPHI2 =  .1232E+07
T =  .00008   PHI = 139.22   PHIDOT =  97.58   G = .0214   PSID =  42.27   PSIDOT =  83.76   PHITOT =   .22
              F23 = 2.5572   F12 = 9.8486   PN =  .3478   PNPSI =  .3478   DPHI2 =  .1230E+07
T =  .00008   PHI = 139.25   PHIDOT = 103.74   G = .0213   PSID =  42.30   PSIDOT =  89.12   PHITOT =   .25
              F23 = 2.5607   F12 = 9.8479   PN =  .3499   PNPSI =  .3499   DPHI2 =  .1238E+07
T =  .00009   PHI = 139.28   PHIDOT = 109.91   G = .0212   PSID =  42.32   PSIDOT =  94.50   PHITOT =   .28
              F23 = 2.5609   F12 = 9.8479   PN =  .3505   PNPSI =  .3505   DPHI2 =  .1235E+07
T =  .00009   PHI = 139.32   PHIDOT = 116.10   G = .0211   PSID =  42.35   PSIDOT =  99.91   PHITOT =   .32
              F23 = 2.5648   F12 = 9.8471   PN =  .3529   PNPSI =  .3529   DPHI2 =  .1245E+07
T =  .00010   PHI = 139.35   PHIDOT = 122.29   G = .0209   PSID =  42.38   PSIDOT = 105.35   PHITOT =   .35
              F23 = 2.5650   F12 = 9.8471   PN =  .3535   PNPSI =  .3535   DPHI2 =  .1242E+07
T =  .00011   PHI = 139.39   PHIDOT = 128.51   G = .0208   PSID =  42.41   PSIDOT = 110.83   PHITOT =   .39
              F23 = 2.5694   F12 = 9.8463   PN =  .3563   PNPSI =  .3563   DPHI2 =  .1252E+07
T =  .00011   PHI = 139.42   PHIDOT = 134.75   G = .0207   PSID =  42.44   PSIDOT = 116.33   PHITOT =   .42
              F23 = 2.5697   F12 = 9.8464   PN =  .3570   PNPSI =  .3570   DPHI2 =  .1249E+07
T =  .00012   PHI = 139.46   PHIDOT = 141.01   G = .0205   PSID =  42.48   PSIDOT = 121.87   PHITOT =   .46
              F23 = 2.5745   F12 = 9.8456   PN =  .3600   PNPSI =  .3600   DPHI2 =  .1260E+07
T =  .00012   PHI = 139.50   PHIDOT = 147.28   G = .0204   PSID =  42.51   PSIDOT = 127.44   PHITOT =   .50
              F23 = 2.5748   F12 = 9.8458   PN =  .3608   PNPSI =  .3608   DPHI2 =  .1257E+07
T =  .00013   PHI = 139.55   PHIDOT = 153.57   G = .0202   PSID =  42.55   PSIDOT = 133.06   PHITOT =   .55
              F23 = 2.5801   F12 = 9.8449   PN =  .3641   PNPSI =  .3641   DPHI2 =  .1269E+07
T =  .00013   PHI = 139.59   PHIDOT = 159.89   G = .0200   PSID =  42.59   PSIDOT = 138.71   PHITOT =   .59
              F23 = 2.5804   F12 = 9.8452   PN =  .3650   PNPSI =  .3650   DPHI2 =  .1265E+07
T =  .00014   PHI = 139.64   PHIDOT = 166.23   G = .0199   PSID =  42.63   PSIDOT = 144.41   PHITOT =   .64
              F23 = 2.5862   F12 = 9.8442   PN =  .3686   PNPSI =  .3686   DPHI2 =  .1278E+07
T =  .00014   PHI = 139.69   PHIDOT = 172.58   G = .0197   PSID =  42.67   PSIDOT = 150.14   PHITOT =   .69
              F23 = 2.5866   F12 = 9.8446   PN =  .3695   PNPSI =  .3695   DPHI2 =  .1274E+07
T =  .00015   PHI = 139.74   PHIDOT = 178.97   G = .0195   PSID =  42.72   PSIDOT = 155.93   PHITOT =   .74
              F23 = 2.5929   F12 = 9.8436   PN =  .3735   PNPSI =  .3735   DPHI2 =  .1288E+07
T =  .00015   PHI = 139.79   PHIDOT = 185.37   G = .0193   PSID =  42.76   PSIDOT = 161.76   PHITOT =   .79
              F23 = 2.5933   F12 = 9.8441   PN =  .3745   PNPSI =  .3745   DPHI2 =  .1284E+07
T =  .00015   PHI = 139.84   PHIDOT = 191.81   G = .0191   PSID =  42.81   PSIDOT = 167.64   PHITOT =   .84
              F23 = 2.6000   F12 = 9.8431   PN =  .3789   PNPSI =  .3789   DPHI2 =  .1299E+07
T =  .00016   PHI = 139.90   PHIDOT = 198.26   G = .0189   PSID =  42.86   PSIDOT = 173.57   PHITOT =   .90
              F23 = 2.6005   F12 = 9.8436   PN =  .3800   PNPSI =  .3800   DPHI2 =  .1294E+07
T =  .00016   PHI = 139.96   PHIDOT = 204.75   G = .0187   PSID =  42.91   PSIDOT = 179.56   PHITOT =   .96
              F23 = 2.6077   F12 = 9.8427   PN =  .3846   PNPSI =  .3846   DPHI2 =  .1310E+07
T =  .00017   PHI = 140.02   PHIDOT = 211.25   G = .0184   PSID =  42.96   PSIDOT = 185.59   PHITOT =  1.02
              F23 = 2.6082   F12 = 9.8433   PN =  .3858   PNPSI =  .3858   DPHI2 =  .1305E+07
T =  .00017   PHI = 140.08   PHIDOT = 217.80   G = .0182   PSID =  43.02   PSIDOT = 191.70   PHITOT =  1.08
              F23 = 2.3558   F12 = 9.8455   PN =  .3877   PNPSI =  .3877   DPHI2 =  .1303E+07
T =  .00018   PHI = 140.14   PHIDOT = 224.32   G = .0180   PSID =  43.07   PSIDOT = 197.82   PHITOT =  1.14
              F23 = 2.3563   F12 = 9.8462   PN =  .3890   PNPSI =  .3890   DPHI2 =  .1297E+07
T =  .00018   PHI = 140.21   PHIDOT = 230.77   G = .0177   PSID =  43.13   PSIDOT = 203.91   PHITOT =  1.21
              F23 = 2.3597   F12 = 9.8514   PN =  .3881   PNPSI =  .3881   DPHI2 =  .1278E+07
```

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A=        .22600     B=        .16800     C=        .13138     ALPHEN=  43.5352     ALPHEX=  29.2981

NT= 4.     CONFIG = 2.

EREST= 0.00   LAMBDA=  92.930   N = 22.

M1 =     .31650E-04   M2 =     .32750E-05   M3 =     .26310E-05   MP =     .16400E-05

IXX1 =    .1222E-05   IEE1 =    .1234E-05   IZZ1 =    .1967E-05   IXE1 =   -.1012E-06   IZX1 =   -.3656E-07   IEZ1 =   -.1770E-

IX2 =    .2944E-07   IY2 =    .2944E-07   IZ2 =    .4026E-07

IXS =    .2038E-06   IYS =    .2038E-06   IZS =    .2125E-07

IXXP =    .1721E-08   IEEP =    .3038E-08   IZZP =    .1951E-07   IXEP =   0.          IZXP =   0.          IEZP =   0.

RC1 =  .0576   RCP = 0.0000   RHOP =  .0227   RPM =30000.   PHI1CD =-120.1340   PSICCD =   0.0000   PHID = 139.0000

PHICUTD = 1485.

MU = .10   MU1 = .10

LU = .285   LL = .285

PSUBD1 = 80.0   PSUBD2 =100.0

NG1 = 64.   NG2 = 36.   NP2 =  9.   NP3 =  8.

CAPRP1 =  .41214   CAPRP2 =  .19039

RP2 =  .05796   RP3 =  .04231

THETA1 =  24.215   THETA2 =  27.326

R1 = .25000   R2 = .31700   R3 = .30900   R4 = .30400

RHO1 = .03075   RHO2 = .01500   RHO3 = .01500

RHOF1 = .0550   RHOF2 = .0294   RHOF3 = .0294   RHOF = .1138

CAPRB1 = .37588   CAPRB2 = .16915   RB2 = .05286   RB3 = .03759

CAPRO1 = .41425   CAPRO2 = .19404   RO2 = .07670   RO3 = .05580

J1 =0.00   J2 =0.00

RX =    .001   RY =    .001   RZ =  20.000

BETA1D = 218.87   BETA2D = 134.90   BETA3D =  92.11
GAMMA2D =-111.47   GAMMA3D =-155.09   GAMMA4D =-198.34

COUPLED MOTION
T = 0.00000   PHI = 139.00   PHIDOT =   0.00   G = .0222   PSID =  42.08   PSIDOT =    0.00   PHITOT =   -.00
              F23 = 2.5071   F12 = 9.7939   PN =  .3383   PNPSI =  .3383   DPHI2 =   .1575E+07
T =  .00001   PHI = 139.00   PHIDOT =   6.35   G = .0222   PSID =  42.08   PSIDOT =    5.42   PHITOT =    .00
              F23 = 2.5447   F12 = 9.8551   PN =  .3378   PNPSI =  .3378   DPHI2 =   .1210E+07
T =  .00001   PHI = 139.00   PHIDOT =  12.40   G = .0222   PSID =  42.08   PSIDOT =   10.58   PHITOT =    .00
              F23 = 2.5446   F12 = 9.8546   PN =  .3378   PNPSI =  .3378   DPHI2 =   .1210E+07
T =  .00002   PHI = 139.01   PHIDOT =  18.45   G = .0222   PSID =  42.09   PSIDOT =   15.74   PHITOT =    .01
              F23 = 2.5451   F12 = 9.8541   PN =  .3382   PNPSI =  .3382   DPHI2 =   .1211E+07
T =  .00002   PHI = 139.01   PHIDOT =  24.51   G = .0222   PSID =  42.09   PSIDOT =   20.91   PHITOT =    .01
              F23 = 2.5450   F12 = 9.8537   PN =  .3383   PNPSI =  .3383   DPHI2 =   .1211E+07
T =  .00003   PHI = 139.02   PHIDOT =  30.56   G = .0222   PSID =  42.10   PSIDOT =   26.08   PHITOT =    .02
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T =  .00019  PHI = 140.27   PHIDOT = 237.16   G = .0175   PSID =  43.19   PSIDOT =  209.99    PHITOT =   1.27
             F23 = 2.3602   F12 = 9.8522   PN =  .3895   PNPSI =  .3895   DPHI2 =   .1272E+07
T =  .00019  PHI = 140.34   PHIDOT = 243.49   G = .0172   PSID =  43.25   PSIDOT =  216.04    PHITOT =   1.34
             F23 = 2.3638   F12 = 9.8577   PN =  .3886   PNPSI =  .3886   DPHI2 =   .1252E+07
T =  .00020  PHI = 140.41   PHIDOT = 249.75   G = .0170   PSID =  43.31   PSIDOT =  222.09    PHITOT =   1.41
             F23 = 2.3643   F12 = 9.8586   PN =  .3900   PNPSI =  .3900   DPHI2 =   .1245E+07
T =  .00020  PHI = 140.45   PHIDOT = 252.67   G = .0168   PSID =  43.34   PSIDOT =  224.93    PHITOT =   1.45
             F23 = 2.6193   F12 = 9.8766   PN =  .3759   PNPSI =  .3759   DPHI2 =   .1156E+07
T =  .00020  PHI = 140.49   PHIDOT = 255.54   G = .0167   PSID =  43.38   PSIDOT =  227.75    PHITOT =   1.49
             F23 = 2.6196   F12 = 9.8771   PN =  .3767   PNPSI =  .3767   DPHI2 =   .1153E+07
T =  .00021  PHI = 140.52   PHIDOT = 258.43   G = .0165   PSID =  43.41   PSIDOT =  230.58    PHITOT =   1.52
             F23 = 2.6243   F12 = 9.8766   PN =  .3796   PNPSI =  .3796   DPHI2 =   .1163E+07
T =  .00021  PHI = 140.56   PHIDOT = 261.33   G = .0164   PSID =  43.44   PSIDOT =  233.44    PHITOT =   1.56
             F23 = 2.6246   F12 = 9.8770   PN =  .3804   PNPSI =  .3804   DPHI2 =   .1160E+07
T =  .00021  PHI = 140.60   PHIDOT = 264.23   G = .0163   PSID =  43.48   PSIDOT =  236.31    PHITOT =   1.60
             F23 = 2.6294   F12 = 9.8765   PN =  .3835   PNPSI =  .3835   DPHI2 =   .1170E+07
T =  .00021  PHI = 140.64   PHIDOT = 267.14   G = .0161   PSID =  43.51   PSIDOT =  239.20    PHITOT =   1.64
             F23 = 2.6297   F12 = 9.8770   PN =  .3842   PNPSI =  .3842   DPHI2 =   .1166E+07
T =  .00022  PHI = 140.67   PHIDOT = 270.06   G = .0160   PSID =  43.54   PSIDOT =  242.11    PHITOT =   1.67
             F23 = 2.6346   F12 = 9.8765   PN =  .3874   PNPSI =  .3874   DPHI2 =   .1177E+07
T =  .00022  PHI = 140.71   PHIDOT = 272.99   G = .0158   PSID =  43.58   PSIDOT =  245.03    PHITOT =   1.71
             F23 = 2.6349   F12 = 9.8770   PN =  .3882   PNPSI =  .3882   DPHI2 =   .1173E+07
T =  .00022  PHI = 140.75   PHIDOT = 275.93   G = .0157   PSID =  43.61   PSIDOT =  247.98    PHITOT =   1.75
             F23 = 2.6399   F12 = 9.8765   PN =  .3915   PNPSI =  .3915   DPHI2 =   .1184E+07
T =  .00022  PHI = 140.79   PHIDOT = 278.87   G = .0155   PSID =  43.65   PSIDOT =  250.94    PHITOT =   1.79
             F23 = 2.6403   F12 = 9.8771   PN =  .3923   PNPSI =  .3923   DPHI2 =   .1180E+07
T =  .00023  PHI = 140.83   PHIDOT = 281.83   G = .0154   PSID =  43.69   PSIDOT =  253.92    PHITOT =   1.83
             F23 = 2.6454   F12 = 9.8766   PN =  .3957   PNPSI =  .3957   DPHI2 =   .1190E+07
T =  .00023  PHI = 140.87   PHIDOT = 284.79   G = .0152   PSID =  43.72   PSIDOT =  256.92    PHITOT =   1.87
             F23 = 2.6458   F12 = 9.8772   PN =  .3966   PNPSI =  .3966   DPHI2 =   .1187E+07
T =  .00023  PHI = 140.91   PHIDOT = 287.76   G = .0151   PSID =  43.76   PSIDOT =  259.95    PHITOT =   1.91
             F23 = 2.6511   F12 = 9.8767   PN =  .4000   PNPSI =  .4000   DPHI2 =   .1197E+07
T =  .00023  PHI = 140.96   PHIDOT = 290.74   G = .0149   PSID =  43.80   PSIDOT =  262.98    PHITOT =   1.96
             F23 = 2.6515   F12 = 9.8773   PN =  .4009   PNPSI =  .4009   DPHI2 =   .1193E+07
T =  .00024  PHI = 141.00   PHIDOT = 293.73   G = .0148   PSID =  43.84   PSIDOT =  266.05    PHITOT =   2.00
             F23 = 2.6569   F12 = 9.8768   PN =  .4045   PNPSI =  .4045   DPHI2 =   .1204E+07
T =  .00024  PHI = 141.04   PHIDOT = 296.72   G = .0146   PSID =  43.87   PSIDOT =  269.13    PHITOT =   2.04
             F23 = 2.6573   F12 = 9.8774   PN =  .4054   PNPSI =  .4054   DPHI2 =   .1200E+07
T =  .00024  PHI = 141.08   PHIDOT = 299.73   G = .0144   PSID =  43.91   PSIDOT =  272.23    PHITOT =   2.08
             F23 = 2.6628   F12 = 9.8770   PN =  .4091   PNPSI =  .4091   DPHI2 =   .1211E+07
T =  .00024  PHI = 141.13   PHIDOT = 302.74   G = .0143   PSID =  43.95   PSIDOT =  275.35    PHITOT =   2.13
             F23 = 2.6632   F12 = 9.8776   PN =  .4101   PNPSI =  .4101   DPHI2 =   .1207E+07
T =  .00025  PHI = 141.17   PHIDOT = 305.76   G = .0141   PSID =  43.99   PSIDOT =  278.49    PHITOT =   2.17
             F23 = 2.6689   F12 = 9.8772   PN =  .4139   PNPSI =  .4139   DPHI2 =   .1218E+07
T =  .00025  PHI = 141.21   PHIDOT = 308.79   G = .0139   PSID =  44.03   PSIDOT =  281.66    PHITOT =   2.21
             F23 = 2.6694   F12 = 9.8779   PN =  .4149   PNPSI =  .4149   DPHI2 =   .1214E+07
T =  .00025  PHI = 141.26   PHIDOT = 311.83   G = .0138   PSID =  44.07   PSIDOT =  284.85    PHITOT =   2.26
             F23 = 2.6751   F12 = 9.8774   PN =  .4188   PNPSI =  .4188   DPHI2 =   .1225E+07
T =  .00025  PHI = 141.30   PHIDOT = 314.88   G = .0136   PSID =  44.11   PSIDOT =  288.05    PHITOT =   2.30
             F23 = 2.6756   F12 = 9.8781   PN =  .4199   PNPSI =  .4199   DPHI2 =   .1221E+07
T =  .00026  PHI = 141.35   PHIDOT = 317.93   G = .0134   PSID =  44.16   PSIDOT =  291.28    PHITOT =   2.35
             F23 = 2.6815   F12 = 9.8777   PN =  .4239   PNPSI =  .4239   DPHI2 =   .1232E+07
T =  .00026  PHI = 141.39   PHIDOT = 321.00   G = .0132   PSID =  44.20   PSIDOT =  294.54    PHITOT =   2.39
             F23 = 2.6820   F12 = 9.8784   PN =  .4250   PNPSI =  .4250   DPHI2 =   .1227E+07
T =  .00026  PHI = 141.44   PHIDOT = 324.07   G = .0131   PSID =  44.24   PSIDOT =  297.81    PHITOT =   2.44
             F23 = 2.4206   F12 = 9.8812   PN =  .4256   PNPSI =  .4256   DPHI2 =   .1220E+07
T =  .00026  PHI = 141.49   PHIDOT = 327.12   G = .0129   PSID =  44.28   PSIDOT =  301.08    PHITOT =   2.49
             F23 = 2.4211   F12 = 9.8820   PN =  .4267   PNPSI =  .4267   DPHI2 =   .1215E+07
T =  .00027  PHI = 141.53   PHIDOT = 330.14   G = .0127   PSID =  44.33   PSIDOT =  304.34    PHITOT =   2.53
             F23 = 2.4236   F12 = 9.8860   PN =  .4261   PNPSI =  .4261   DPHI2 =   .1201E+07
T =  .00027  PHI = 141.58   PHIDOT = 333.14   G = .0125   PSID =  44.37   PSIDOT =  307.60    PHITOT =   2.58
             F23 = 2.4240   F12 = 9.8868   PN =  .4272   PNPSI =  .4272   DPHI2 =   .1196E+07
T =  .00027  PHI = 141.63   PHIDOT = 336.12   G = .0124   PSID =  44.41   PSIDOT =  310.85    PHITOT =   2.63
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T =  .00027   PHI = 141.68   PHIDOT = 339.07   G = .0122   PSID =  44.46   PSIDOT =  314.10   PHITOT =  2.68
              F23 = 2.4271   F12 = 9.8918   PN =  .4277   PNPSI =  .4277   DPHI2 =  .1176E+07
T =  .00028   PHI = 141.73   PHIDOT = 342.00   G = .0120   PSID =  44.50   PSIDOT =  317.33   PHITOT =  2.73
              F23 = 2.4297   F12 = 9.8960   PN =  .4271   PNPSI =  .4271   DPHI2 =  .1181E+07
T =  .00028   PHI = 141.78   PHIDOT = 344.90   G = .0118   PSID =  44.55   PSIDOT =  320.56   PHITOT =  2.78
              F23 = 2.4302   F12 = 9.8968   PN =  .4283   PNPSI =  .4283   DPHI2 =  .1156E+07
T =  .00028   PHI = 141.82   PHIDOT = 347.58   G = .0116   PSID =  44.60   PSIDOT =  323.59   PHITOT =  2.82
              F23 = 2.6883   F12 = 9.9149   PN =  .4120   PNPSI =  .4120   DPHI2 =  .1060E+07
T =  .00028   PHI = 141.87   PHIDOT = 350.20   G = .0114   PSID =  44.64   PSIDOT =  326.60   PHITOT =  2.87
              F23 = 2.6888   F12 = 9.9158   PN =  .4132   PNPSI =  .4132   DPHI2 =  .1054E+07
T =  .00029   PHI = 141.92   PHIDOT = 352.85   G = .0112   PSID =  44.69   PSIDOT =  329.64   PHITOT =  2.92
              F23 = 2.6954   F12 = 9.9154   PN =  .4176   PNPSI =  .4176   DPHI2 =  .1067E+07
T =  .00029   PHI = 141.98   PHIDOT = 355.49   G = .0110   PSID =  44.74   PSIDOT =  332.69   PHITOT =  2.98
              F23 = 2.6960   F12 = 9.9163   PN =  .4188   PNPSI =  .4188   DPHI2 =  .1061E+07
T =  .00029   PHI = 142.03   PHIDOT = 358.15   G = .0108   PSID =  44.78   PSIDOT =  335.78   PHITOT =  3.03
              F23 = 2.7027   F12 = 9.9160   PN =  .4234   PNPSI =  .4234   DPHI2 =  .1074E+07
T =  .00029   PHI = 142.08   PHIDOT = 360.82   G = .0106   PSID =  44.83   PSIDOT =  338.88   PHITOT =  3.08
              F23 = 2.7033   F12 = 9.9169   PN =  .4246   PNPSI =  .4246   DPHI2 =  .1068E+07
T =  .00030   PHI = 142.13   PHIDOT = 363.50   G = .0104   PSID =  44.88   PSIDOT =  342.02   PHITOT =  3.13
              F23 = 2.7101   F12 = 9.9166   PN =  .4294   PNPSI =  .4294   DPHI2 =  .1081E+07
T =  .00030   PHI = 142.18   PHIDOT = 366.18   G = .0102   PSID =  44.93   PSIDOT =  345.17   PHITOT =  3.18
              F23 = 2.7107   F12 = 9.9175   PN =  .4306   PNPSI =  .4306   DPHI2 =  .1075E+07
T =  .00030   PHI = 142.24   PHIDOT = 368.87   G = .0100   PSID =  44.98   PSIDOT =  348.36   PHITOT =  3.24
              F23 = 2.7177   F12 = 9.9172   PN =  .4355   PNPSI =  .4355   DPHI2 =  .1088E+07
T =  .00030   PHI = 142.29   PHIDOT = 371.57   G = .0098   PSID =  45.03   PSIDOT =  351.56   PHITOT =  3.29
              F23 = 2.7184   F12 = 9.9182   PN =  .4368   PNPSI =  .4368   DPHI2 =  .1082E+07
T =  .00031   PHI = 142.34   PHIDOT = 374.28   G = .0096   PSID =  45.08   PSIDOT =  354.80   PHITOT =  3.34
              F23 = 2.7255   F12 = 9.9179   PN =  .4418   PNPSI =  .4418   DPHI2 =  .1094E+07
T =  .00031   PHI = 142.40   PHIDOT = 377.00   G = .0094   PSID =  45.13   PSIDOT =  358.06   PHITOT =  3.40
              F23 = 2.7261   F12 = 9.9190   PN =  .4431   PNPSI =  .4431   DPHI2 =  .1088E+07
T =  .00031   PHI = 142.45   PHIDOT = 379.72   G = .0092   PSID =  45.18   PSIDOT =  361.35   PHITOT =  3.45
              F23 = 2.7334   F12 = 9.9187   PN =  .4482   PNPSI =  .4482   DPHI2 =  .1101E+07
T =  .00031   PHI = 142.50   PHIDOT = 382.45   G = .0090   PSID =  45.24   PSIDOT =  364.66   PHITOT =  3.50
              F23 = 2.7341   F12 = 9.9198   PN =  .4496   PNPSI =  .4496   DPHI2 =  .1095E+07
T =  .00032   PHI = 142.56   PHIDOT = 385.20   G = .0088   PSID =  45.29   PSIDOT =  368.01   PHITOT =  3.56
              F23 = 2.7415   F12 = 9.9196   PN =  .4549   PNPSI =  .4549   DPHI2 =  .1107E+07
T =  .00032   PHI = 142.61   PHIDOT = 387.94   G = .0086   PSID =  45.34   PSIDOT =  371.38   PHITOT =  3.61
              F23 = 2.7422   F12 = 9.9207   PN =  .4563   PNPSI =  .4563   DPHI2 =  .1101E+07
T =  .00032   PHI = 142.67   PHIDOT = 390.70   G = .0083   PSID =  45.39   PSIDOT =  374.78   PHITOT =  3.67
              F23 = 2.7498   F12 = 9.9205   PN =  .4618   PNPSI =  .4618   DPHI2 =  .1114E+07
T =  .00032   PHI = 142.73   PHIDOT = 393.46   G = .0081   PSID =  45.45   PSIDOT =  378.20   PHITOT =  3.73
              F23 = 2.7505   F12 = 9.9217   PN =  .4633   PNPSI =  .4633   DPHI2 =  .1107E+07
T =  .00033   PHI = 142.78   PHIDOT = 396.23   G = .0079   PSID =  45.50   PSIDOT =  381.66   PHITOT =  3.78
              F23 = 2.7582   F12 = 9.9215   PN =  .4688   PNPSI =  .4688   DPHI2 =  .1120E+07
T =  .00033   PHI = 142.84   PHIDOT = 399.01   G = .0077   PSID =  45.56   PSIDOT =  385.14   PHITOT =  3.84
              F23 = 2.7590   F12 = 9.9227   PN =  .4704   PNPSI =  .4704   DPHI2 =  .1113E+07
T =  .00033   PHI = 142.90   PHIDOT = 401.78   G = .0075   PSID =  45.61   PSIDOT =  388.64   PHITOT =  3.90
              F23 = 2.4903   F12 = 9.9272   PN =  .4705   PNPSI =  .4705   DPHI2 =  .1098E+07
T =  .00033   PHI = 142.96   PHIDOT = 404.53   G = .0072   PSID =  45.67   PSIDOT =  392.14   PHITOT =  3.96
              F23 = 2.4910   F12 = 9.9285   PN =  .4721   PNPSI =  .4721   DPHI2 =  .1091E+07
T =  .00034   PHI = 143.01   PHIDOT = 407.24   G = .0070   PSID =  45.73   PSIDOT =  395.62   PHITOT =  4.01
              F23 = 2.4942   F12 = 9.9337   PN =  .4713   PNPSI =  .4713   DPHI2 =  .1073E+07
T =  .00034   PHI = 143.07   PHIDOT = 409.92   G = .0068   PSID =  45.78   PSIDOT =  399.11   PHITOT =  4.07
              F23 = 2.4949   F12 = 9.9350   PN =  .4729   PNPSI =  .4729   DPHI2 =  .1065E+07
T =  .00034   PHI = 143.13   PHIDOT = 412.56   G = .0065   PSID =  45.84   PSIDOT =  402.57   PHITOT =  4.13
              F23 = 2.4980   F12 = 9.9403   PN =  .4721   PNPSI =  .4721   DPHI2 =  .1047E+07
T =  .00034   PHI = 143.19   PHIDOT = 415.18   G = .0063   PSID =  45.90   PSIDOT =  406.04   PHITOT =  4.19
              F23 = 2.4988   F12 = 9.9416   PN =  .4738   PNPSI =  .4738   DPHI2 =  .1039E+07
T =  .00035   PHI = 143.22   PHIDOT = 416.38   G = .0062   PSID =  45.93   PSIDOT =  407.67   PHITOT =  4.22
              F23 = 2.7655   F12 = 9.9596   PN =  .4561   PNPSI =  .4561   DPHI2 =  .9483E+06
T =  .00035   PHI = 143.25   PHIDOT = 417.56   G = .0061   PSID =  45.96   PSIDOT =  409.29   PHITOT =  4.25
              F23 = 2.7659   F12 = 9.9603   PN =  .4569   PNPSI =  .4569   DPHI2 =  .9447E+06
T =  .00035   PHI = 143.28   PHIDOT = 418.74   G = .0060   PSID =  45.99   PSIDOT =  410.92   PHITOT =  4.28
              F23 = 2.7700   F12 = 9.9603   PN =  .4598   PNPSI =  .4598   DPHI2 =  .9512E+06
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T =  .00035  PHI = 143.31   PHIDOT = 419.92   G = .0058   PSID =  46.02   PSIDOT =  412.55    PHITOT =   4.31
             F23 = 2.7703   F12 = 9.9609   PN = .4606   PNPSI =  .4606   DPHI2 =   .9475E+06
T =  .00035  PHI = 143.34   PHIDOT = 421.11   G = .0057   PSID =  46.04   PSIDOT =  414.20    PHITOT =   4.34
             F23 = 2.7745   F12 = 9.9609   PN = .4636   PNPSI =  .4636   DPHI2 =   .9540E+06
T =  .00035  PHI = 143.37   PHIDOT = 422.30   G = .0056   PSID =  46.07   PSIDOT =  415.85    PHITOT =   4.37
             F23 = 2.7749   F12 = 9.9616   PN = .4644   PNPSI =  .4644   DPHI2 =   .9503E+06
T =  .00035  PHI = 143.40   PHIDOT = 423.49   G = .0055   PSID =  46.10   PSIDOT =  417.51    PHITOT =   4.40
             F23 = 2.7790   F12 = 9.9616   PN = .4674   PNPSI =  .4674   DPHI2 =   .9568E+06
T =  .00035  PHI = 143.43   PHIDOT = 424.68   G = .0054   PSID =  46.13   PSIDOT =  419.17    PHITOT =   4.43
             F23 = 2.7794   F12 = 9.9622   PN = .4683   PNPSI =  .4683   DPHI2 =   .9530E+06
T =  .00036  PHI = 143.46   PHIDOT = 425.87   G = .0053   PSID =  46.16   PSIDOT =  420.84    PHITOT =   4.46
             F23 = 2.7836   F12 = 9.9622   PN = .4713   PNPSI =  .4713   DPHI2 =   .9594E+06
T =  .00036  PHI = 143.49   PHIDOT = 427.06   G = .0051   PSID =  46.19   PSIDOT =  422.52    PHITOT =   4.49
             F23 = 2.7840   F12 = 9.9629   PN = .4722   PNPSI =  .4722   DPHI2 =   .9556E+06
T =  .00036  PHI = 143.52   PHIDOT = 428.26   G = .0050   PSID =  46.22   PSIDOT =  424.21    PHITOT =   4.52
             F23 = 2.7882   F12 = 9.9629   PN = .4752   PNPSI =  .4752   DPHI2 =   .9620E+06
T =  .00036  PHI = 143.55   PHIDOT = 429.45   G = .0049   PSID =  46.26   PSIDOT =  425.91    PHITOT =   4.55
             F23 = 2.7886   F12 = 9.9636   PN = .4761   PNPSI =  .4761   DPHI2 =   .9581E+06
T =  .00036  PHI = 143.58   PHIDOT = 430.65   G = .0048   PSID =  46.29   PSIDOT =  427.61    PHITOT =   4.58
             F23 = 2.7929   F12 = 9.9637   PN = .4792   PNPSI =  .4792   DPHI2 =   .9645E+06
T =  .00036  PHI = 143.61   PHIDOT = 431.85   G = .0047   PSID =  46.32   PSIDOT =  429.32    PHITOT =   4.61
             F23 = 2.7933   F12 = 9.9644   PN = .4801   PNPSI =  .4801   DPHI2 =   .9606E+06
T =  .00036  PHI = 143.65   PHIDOT = 433.05   G = .0045   PSID =  46.35   PSIDOT =  431.04    PHITOT =   4.65
             F23 = 2.7976   F12 = 9.9644   PN = .4833   PNPSI =  .4833   DPHI2 =   .9670E+06
T =  .00036  PHI = 143.68   PHIDOT = 434.26   G = .0044   PSID =  46.38   PSIDOT =  432.77    PHITOT =   4.68
             F23 = 2.7981   F12 = 9.9651   PN = .4841   PNPSI =  .4841   DPHI2 =   .9629E+06
T =  .00037  PHI = 143.71   PHIDOT = 435.46   G = .0043   PSID =  46.41   PSIDOT =  434.50    PHITOT =   4.71
             F23 = 2.8024   F12 = 9.9652   PN = .4874   PNPSI =  .4874   DPHI2 =   .9693E+06
T =  .00037  PHI = 143.74   PHIDOT = 436.67   G = .0042   PSID =  46.44   PSIDOT =  436.24    PHITOT =   4.74
             F23 = 2.8028   F12 = 9.9659   PN = .4883   PNPSI =  .4883   DPHI2 =   .9652E+06
T =  .00037  PHI = 143.77   PHIDOT = 437.87   G = .0040   PSID =  46.47   PSIDOT =  437.99    PHITOT =   4.77
             F23 = 2.8020   F12 = 9.1027   PN = .4907   PNPSI =  .4907   DPHI2 =   .9679E+06
T =  .00037  PHI = 143.80   PHIDOT = 439.08   G = .0039   PSID =  46.50   PSIDOT =  439.75    PHITOT =   4.80
             F23 = 2.8025   F12 = 9.1034   PN = .4916   PNPSI =  .4916   DPHI2 =   .9637E+06
T =  .00037  PHI = 143.86   PHIDOT = 441.49   G = .0037   PSID =  46.57   PSIDOT =  443.27    PHITOT =   4.86
             F23 = 2.8012   F12 = 9.1007   PN = .4966   PNPSI =  .4966   DPHI2 =   .9692E+06
T =  .00037  PHI = 143.93   PHIDOT = 443.89   G = .0034   PSID =  46.63   PSIDOT =  446.82    PHITOT =   4.93
             F23 = 2.8022   F12 = 9.1021   PN = .4985   PNPSI =  .4985   DPHI2 =   .9605E+06
T =  .00038  PHI = 143.99   PHIDOT = 446.29   G = .0032   PSID =  46.69   PSIDOT =  450.40    PHITOT =   4.99
             F23 = 2.8009   F12 = 9.0995   PN = .5035   PNPSI =  .5036   DPHI2 =   .9658E+06
T =  .00038  PHI = 144.06   PHIDOT = 448.68   G = .0029   PSID =  46.76   PSIDOT =  453.99    PHITOT =   5.06
             F23 = 2.8019   F12 = 9.1010   PN = .5056   PNPSI =  .5056   DPHI2 =   .9569E+06
T =  .00038  PHI = 144.12   PHIDOT = 451.07   G = .0027   PSID =  46.82   PSIDOT =  457.61    PHITOT =   5.12
             F23 = 2.8007   F12 = 9.0983   PN = .5108   PNPSI =  .5108   DPHI2 =   .9620E+06
T =  .00038  PHI = 144.19   PHIDOT = 453.45   G = .0024   PSID =  46.89   PSIDOT =  461.25    PHITOT =   5.19
             F23 = 2.8017   F12 = 9.0999   PN = .5128   PNPSI =  .5128   DPHI2 =   .9527E+06
T =  .00039  PHI = 144.25   PHIDOT = 455.82   G = .0021   PSID =  46.96   PSIDOT =  464.90    PHITOT =   5.25
             F23 = 2.5201   F12 = 9.1018   PN = .5114   PNPSI =  .5114   DPHI2 =   .9285E+06
T =  .00039  PHI = 144.32   PHIDOT = 458.14   G = .0019   PSID =  47.02   PSIDOT =  468.54    PHITOT =   5.32
             F23 = 2.5210   F12 = 9.1033   PN = .5135   PNPSI =  .5135   DPHI2 =   .9191E+06
T =  .00039  PHI = 144.38   PHIDOT = 460.41   G = .0016   PSID =  47.09   PSIDOT =  472.15    PHITOT =   5.38
             F23 = 2.5151   F12 = 9.1060   PN = .5109   PNPSI =  .5109   DPHI2 =   .8901E+06
T =  .00039  PHI = 144.45   PHIDOT = 462.64   G = .0014   PSID =  47.16   PSIDOT =  475.75    PHITOT =   5.45
             F23 = 2.5160   F12 = 9.1076   PN = .5130   PNPSI =  .5130   DPHI2 =   .8806E+06
T =  .00040  PHI = 144.51   PHIDOT = 464.82   G = .0011   PSID =  47.23   PSIDOT =  479.33    PHITOT =   5.51
             F23 = 2.5990   F12 = 9.9352   PN = .4613   PNPSI =  .4613   DPHI2 =   .6439E+06
T =  .00040  PHI = 144.58   PHIDOT = 466.90   G = .0008   PSID =  47.30   PSIDOT =  482.84    PHITOT =   5.58
             F23 = 2.6000   F12 = 9.9368   PN = .4632   PNPSI =  .4632   DPHI2 =   .6350E+06
T =  .00040  PHI = 144.65   PHIDOT = 468.49   G = .0006   PSID =  47.37   PSIDOT =  485.86    PHITOT =   5.65
             F23 = 2.6091   F12 = 9.9373   PN = .4699   PNPSI =  .4699   DPHI2 =   .6467E+06
T =  .00040  PHI = 144.72   PHIDOT = 470.08   G = .0003   PSID =  47.44   PSIDOT =  488.92    PHITOT =   5.72
             F23 = 2.6100   F12 = 9.9389   PN = .4717   PNPSI =  .4717   DPHI2 =   .6381E+06
T =  .00041  PHI = 144.78   PHIDOT = 471.68   G = .0000   PSID =  47.51   PSIDOT =  492.01    PHITOT =   5.78
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T =  .00041   PHI = 144.85   PHIDOT = 473.28   G =-.0003   PSID =  47.58   PSIDOT =  495.12   PHITOT =   5.85
              F23 = 2.6202   F12 = 9.9410   PN =  .4804   PNPSI =  .4804   DPHI2 =   .6407E+06

FREE MOTION

T =  .00041   PHI = 210.30   PHIDOT = 473.28   PSI = 314.65   PSIDOT =  495.12   PHITOT =   5.85
              FF12 =  9.562   FF23 =  2.392
T =  .00041   PHI = 210.37   PHIDOT = 480.90   PSI = 314.72   PSIDOT =  493.11   PHITOT =   5.92
              FF12 =  9.537   FF23 =  2.423
T =  .00041   PHI = 210.44   PHIDOT = 488.63   PSI = 314.79   PSIDOT =  491.09   PHITOT =   5.99
              FF12 =  9.537   FF23 =  2.423
T =  .00042   PHI = 210.51   PHIDOT = 496.43   PSI = 314.86   PSIDOT =  489.07   PHITOT =   6.06
              FF12 =  9.539   FF23 =  2.189
T =  .00042   PHI = 210.58   PHIDOT = 504.22   PSI = 314.93   PSIDOT =  487.06   PHITOT =   6.13
              FF12 =  9.539   FF23 =  2.189
T =  .00042   PHI = 210.66   PHIDOT = 511.97   PSI = 315.00   PSIDOT =  485.05   PHITOT =   6.20
              FF12 =  9.546   FF23 =  2.193
T =  .00042   PHI = 210.73   PHIDOT = 519.70   PSI = 315.07   PSIDOT =  483.03   PHITOT =   6.28
              FF12 =  9.546   FF23 =  2.193
T =  .00043   PHI = 210.81   PHIDOT = 527.39   PSI = 315.14   PSIDOT =  481.02   PHITOT =   6.35
              FF12 =  9.583   FF23 =  2.434
T =  .00043   PHI = 210.88   PHIDOT = 535.06   PSI = 315.20   PSIDOT =  479.00   PHITOT =   6.43
              FF12 =  9.583   FF23 =  2.434
T =  .00043   PHI = 210.96   PHIDOT = 542.31   PSI = 315.27   PSIDOT =  476.99   PHITOT =   6.51
              FF12 =  9.578   FF23 =  2.441
T =  .00043   PHI = 211.04   PHIDOT = 549.60   PSI = 315.34   PSIDOT =  474.97   PHITOT =   6.58
              FF12 =  9.578   FF23 =  2.441
T =  .00044   PHI = 211.12   PHIDOT = 556.97   PSI = 315.41   PSIDOT =  472.96   PHITOT =   6.66
              FF12 =  9.573   FF23 =  2.447
T =  .00044   PHI = 211.20   PHIDOT = 564.38   PSI = 315.48   PSIDOT =  470.95   PHITOT =   6.74
              FF12 =  9.573   FF23 =  2.447
T =  .00044   PHI = 211.28   PHIDOT = 571.86   PSI = 315.54   PSIDOT =  468.94   PHITOT =   6.82
              FF12 =  9.567   FF23 =  2.454
T =  .00044   PHI = 211.36   PHIDOT = 579.40   PSI = 315.61   PSIDOT =  466.92   PHITOT =   6.91
              FF12 =  9.568   FF23 =  2.454
T =  .00045   PHI = 211.44   PHIDOT = 587.01   PSI = 315.68   PSIDOT =  464.91   PHITOT =   6.99
              FF12 =  9.562   FF23 =  2.461
T =  .00045   PHI = 211.53   PHIDOT = 594.67   PSI = 315.74   PSIDOT =  462.90   PHITOT =   7.07
              FF12 =  9.562   FF23 =  2.462
T =  .00045   PHI = 211.62   PHIDOT = 602.41   PSI = 315.81   PSIDOT =  460.89   PHITOT =   7.16
              FF12 =  9.556   FF23 =  2.469
T =  .00045   PHI = 211.70   PHIDOT = 610.20   PSI = 315.88   PSIDOT =  458.87   PHITOT =   7.25
              FF12 =  9.557   FF23 =  2.469
T =  .00046   PHI = 211.79   PHIDOT = 618.08   PSI = 315.94   PSIDOT =  456.86   PHITOT =   7.34
              FF12 =  9.551   FF23 =  2.476
VP=  47.221   VS= -71.411

IMPACT

              PHI= 211.790   PHIDOT= 112.777   PSI= 315.942   PSIDOT=-126.064   PHITOT=   7.335
VP= -13.030   VS= -13.030

COUPLED MOTION
T =  .00046   PHI = 211.79   PHIDOT = 112.78   G =-.0115   PSID = 315.89   PSIDOT = -126.30   PHITOT =   7.34
              F23 = 2.6939   F12 = 9.9052   PN =  .3977   PNPSI =  .3977   DPHI2 =   .1109E+07
T =  .00047   PHI = 211.86   PHIDOT = 124.00   G =-.0113   PSID = 315.81   PSIDOT = -138.20   PHITOT =   7.40
              F23 = 2.4322   F12 = 9.9046   PN =  .3972   PNPSI =  .3972   DPHI2 =   .1128E+07
T =  .00048   PHI = 211.93   PHIDOT = 135.39   G =-.0110   PSID = 315.73   PSIDOT = -150.08   PHITOT =   7.48
              F23 = 2.4308   F12 = 9.9022   PN =  .3954   PNPSI =  .3954   DPHI2 =   .1143E+07
T =  .00049   PHI = 212.01   PHIDOT = 146.85   G =-.0108   PSID = 315.64   PSIDOT = -161.85   PHITOT =   7.56
              F23 = 2.4327   F12 = 9.9050   PN =  .3902   PNPSI =  .3902   DPHI2 =   .1145E+07
T =  .00050   PHI = 212.10   PHIDOT = 158.43   G =-.0105   PSID = 315.55   PSIDOT = -173.51   PHITOT =   7.65
              F23 = 2.4311   F12 = 9.9023   PN =  .3880   PNPSI =  .3880   DPHI2 =   .1162E+07
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T =  .00050  PHI = 212.12  PHIDOT = 161.15   G =-.0104  PSID = 315.52  PSIDOT = -176.20  PHITOT =  7.67
             F23 = 2.6916  F12 = 9.9207  PN =  .3682  PNPSI =  .3682  DPHI2 =  .1080E+07
T =  .00050  PHI = 212.15  PHIDOT = 163.85   G =-.0103  PSID = 315.50  PSIDOT = -178.85  PHITOT =  7.69
             F23 = 2.6912  F12 = 9.9200  PN =  .3677  PNPSI =  .3677  DPHI2 =  .1085E+07
T =  .00050  PHI = 212.17  PHIDOT = 166.57   G =-.0102  PSID = 315.47  PSIDOT = -181.51  PHITOT =  7.72
             F23 = 2.6937  F12 = 9.9190  PN =  .3688  PNPSI =  .3688  DPHI2 =  .1096E+07
T =  .00051  PHI = 212.19  PHIDOT = 169.32   G =-.0101  PSID = 315.44  PSIDOT = -184.18  PHITOT =  7.74
             F23 = 2.6933  F12 = 9.9183  PN =  .3682  PNPSI =  .3682  DPHI2 =  .1101E+07
T =  .00051  PHI = 21[illegible].22  PHIDOT = 172.08   G =-.0101  PSID = 315.42  PSIDOT = -186.86  PHITOT =  7.76
             F23 = 2.6959  F12 = 9.9172  PN =  .3693  PNPSI =  .3693  DPHI2 =  .1113E+07
T =  .00051  PHI = 212.24  PHIDOT = 174.86   G =-.0100  PSID = 315.39  PSIDOT = -189.54  PHITOT =  7.79
             F23 = 2.6954  F12 = 9.9166  PN =  .3687  PNPSI =  .3687  DPHI2 =  .1118E+07
T =  .00051  PHI = 212.27  PHIDOT = 177.67   G =-.0099  PSID = 315.36  PSIDOT = -192.23  PHITOT =  7.81
             F23 = 2.6981  F12 = 9.9154  PN =  .3698  PNPSI =  .3698  DPHI2 =  .1130E+07
T =  .00052  PHI = 212.29  PHIDOT = 180.49   G =-.0098  PSID = 315.33  PSIDOT = -194.93  PHITOT =  7.84
             F23 = 2.6976  F12 = 9.9147  PN =  .3692  PNPSI =  .3692  DPHI2 =  .1135E+07
T =  .00052  PHI = 212.32  PHIDOT = 183.34   G =-.0097  PSID = 315.31  PSIDOT = -197.63  PHITOT =  7.87
             F23 = 2.7004  F12 = 9.9136  PN =  .3704  PNPSI =  .3704  DPHI2 =  .1148E+07
T =  .00052  PHI = 212.35  PHIDOT = 186.21   G =-.0096  PSID = 315.28  PSIDOT = -200.34  PHITOT =  7.89
             F23 = 2.6999  F12 = 9.9128  PN =  .3697  PNPSI =  .3697  DPHI2 =  .1153E+07
T =  .00052  PHI = 212.37  PHIDOT = 189.11   G =-.0095  PSID = 315.25  PSIDOT = -203.07  PHITOT =  7.92
             F23 = 2.7028  F12 = 9.9116  PN =  .3709  PNPSI =  .3709  DPHI2 =  .1167E+07
T =  .00053  PHI = 212.40  PHIDOT = 192.02   G =-.0094  PSID = 315.22  PSIDOT = -205.79  PHITOT =  7.95
             F23 = 2.7023  F12 = 9.9109  PN =  .3702  PNPSI =  .3702  DPHI2 =  .1172E+07
T =  .00053  PHI = 212.43  PHIDOT = 194.97   G =-.0094  PSID = 315.19  PSIDOT = -208.53  PHITOT =  7.97
             F23 = 2.7052  F12 = 9.9096  PN =  .3714  PNPSI =  .3714  DPHI2 =  .1186E+07
T =  .00053  PHI = 212.46  PHIDOT = 197.93   G =-.0093  PSID = 315.16  PSIDOT = -211.27  PHITOT =  8.00
             F23 = 2.7047  F12 = 9.9088  PN =  .3707  PNPSI =  .3707  DPHI2 =  .1191E+07
T =  .00053  PHI = 212.49  PHIDOT = 200.93   G =-.0092  PSID = 315.13  PSIDOT = -214.02  PHITOT =  8.03
             F23 = 2.7077  F12 = 9.9075  PN =  .3719  PNPSI =  .3719  DPHI2 =  .1206E+07
T =  .00054  PHI = 212.51  PHIDOT = 203.94   G =-.0091  PSID = 315.10  PSIDOT = -216.78  PHITOT =  8.06
             F23 = 2.7072  F12 = 9.9067  PN =  .3712  PNPSI =  .3712  DPHI2 =  .1212E+07
T =  .00054  PHI = 212.54  PHIDOT = 206.98   G =-.0090  PSID = 315.07  PSIDOT = -219.55  PHITOT =  8.09
             F23 = 2.7103  F12 = 9.9054  PN =  .3724  PNPSI =  .3724  DPHI2 =  .1227E+07
T =  .00054  PHI = 212.57  PHIDOT = 210.05   G =-.0089  PSID = 315.04  PSIDOT = -222.32  PHITOT =  8.12
             F23 = 2.7097  F12 = 9.9045  PN =  .3717  PNPSI =  .3717  DPHI2 =  .1233E+07
T =  .00054  PHI = 212.60  PHIDOT = 213.15   G =-.0088  PSID = 315.00  PSIDOT = -225.11  PHITOT =  8.15
             F23 = 2.7129  F12 = 9.9031  PN =  .3729  PNPSI =  .3729  DPHI2 =  .1248E+07
T =  .00055  PHI = 212.63  PHIDOT = 216.27   G =-.0087  PSID = 314.97  PSIDOT = -227.90  PHITOT =  8.18
             F23 = 2.7123  F12 = 9.9023  PN =  .3722  PNPSI =  .3722  DPHI2 =  .1254E+07
T =  .00055  PHI = 212.67  PHIDOT = 219.42   G =-.0086  PSID = 314.94  PSIDOT = -230.70  PHITOT =  8.21
             F23 = 2.7156  F12 = 9.9008  PN =  .3734  PNPSI =  .3734  DPHI2 =  .1271E+07
T =  .00055  PHI = 212.70  PHIDOT = 222.60   G =-.0084  PSID = 314.91  PSIDOT = -233.50  PHITOT =  8.24
             F23 = 2.7150  F12 = 9.8999  PN =  .3726  PNPSI =  .3726  DPHI2 =  .1277E+07
T =  .00055  PHI = 212.73  PHIDOT = 225.81   G =-.0083  PSID = 314.87  PSIDOT = -236.32  PHITOT =  8.28
             F23 = 2.7184  F12 = 9.8984  PN =  .3739  PNPSI =  .3739  DPHI2 =  .1294E+07
T =  .00056  PHI = 212.76  PHIDOT = 229.04   G =-.0082  PSID = 314.84  PSIDOT = -239.14  PHITOT =  8.31
             F23 = 2.7177  F12 = 9.8975  PN =  .3731  PNPSI =  .3731  DPHI2 =  .1301E+07
T =  .00056  PHI = 212.80  PHIDOT = 232.31   G =-.0081  PSID = 314.80  PSIDOT = -241.98  PHITOT =  8.34
             F23 = 2.7212  F12 = 9.8959  PN =  .3744  PNPSI =  .3744  DPHI2 =  .1318E+07
T =  .00056  PHI = 212.83  PHIDOT = 235.60   G =-.0080  PSID = 314.77  PSIDOT = -244.82  PHITOT =  8.37
             F23 = 2.7206  F12 = 9.8949  PN =  .3735  PNPSI =  .3735  DPHI2 =  .1325E+07
T =  .00056  PHI = 212.86  PHIDOT = 238.93   G =-.0079  PSID = 314.73  PSIDOT = -247.67  PHITOT =  8.41
             F23 = 2.7241  F12 = 9.8933  PN =  .3749  PNPSI =  .3749  DPHI2 =  .1343E+07
T =  .00057  PHI = 212.90  PHIDOT = 242.29   G =-.0078  PSID = 314.70  PSIDOT = -250.52  PHITOT =  8.44
             F23 = 2.7234  F12 = 9.8922  PN =  .3739  PNPSI =  .3739  DPHI2 =  .1350E+07
T =  .00057  PHI = 212.93  PHIDOT = 245.68   G =-.0077  PSID = 314.66  PSIDOT = -253.39  PHITOT =  8.48
             F23 = 2.7270  F12 = 9.8904  PN =  .3753  PNPSI =  .3753  DPHI2 =  .1369E+07
T =  .00057  PHI = 212.97  PHIDOT = 249.11   G =-.0075  PSID = 314.62  PSIDOT = -256.26  PHITOT =  8.51
             F23 = 2.7263  F12 = 9.8892  PN =  .3743  PNPSI =  .3743  DPHI2 =  .1376E+07
T =  .00057  PHI = 213.00  PHIDOT = 252.56   G =-.0074  PSID = 314.59  PSIDOT = -259.15  PHITOT =  8.55
             F23 = 2.7300  F12 = 9.8873  PN =  .3757  PNPSI =  .3757  DPHI2 =  .1396E+07
T =  .00058  PHI = 213.04  PHIDOT = 256.05   G =-.0073  PSID = 314.55  PSIDOT = -262.04  PHITOT =  8.59
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T =  .00058   PHI = 213.08   PHIDOT = 259.58   G =-.0072   PSID = 314.51   PSIDOT = -264.94   PHITOT =   8.62
              F23 = 2.4628   F12 = 9.8848   PN =  .3753   PNPSI =  .3753   DPHI2 =  .1420E+07
T =  .00058   PHI = 213.11   PHIDOT = 263.14   G =-.0070   PSID = 314.47   PSIDOT = -267.85   PHITOT =   8.66
              F23 = 2.4621   F12 = 9.8836   PN =  .3742   PNPSI =  .3742   DPHI2 =  .1428E+07
T =  .00058   PHI = 213.15   PHIDOT = 266.72   G =-.0069   PSID = 314.44   PSIDOT = -270.74   PHITOT =   8.70
              F23 = 2.4630   F12 = 9.8850   PN =  .3717   PNPSI =  .3717   DPHI2 =  .1428E+07
T =  .00059   PHI = 213.19   PHIDOT = 270.30   G =-.0068   PSID = 314.40   PSIDOT = -273.62   PHITOT =   8.74
              F23 = 2.4623   F12 = 9.8837   PN =  .3706   PNPSI =  .3706   DPHI2 =  .1436E+07
T =  .00059   PHI = 213.23   PHIDOT = 273.90   G =-.0067   PSID = 314.36   PSIDOT = -276.48   PHITOT =   8.78
              F23 = 2.4632   F12 = 9.8852   PN =  .3679   PNPSI =  .3679   DPHI2 =  .1437E+07
T =  .00059   PHI = 213.27   PHIDOT = 277.51   G =-.0065   PSID = 314.32   PSIDOT = -279.32   PHITOT =   8.81
              F23 = 2.4624   F12 = 9.8839   PN =  .3668   PNPSI =  .3668   DPHI2 =  .1446E+07
T =  .00059   PHI = 213.31   PHIDOT = 281.13   G =-.0064   PSID = 314.28   PSIDOT = -282.15   PHITOT =   8.85
              F23 = 2.4633   F12 = 9.8854   PN =  .3641   PNPSI =  .3641   DPHI2 =  .1446E+07
T =  .00060   PHI = 213.35   PHIDOT = 284.76   G =-.0062   PSID = 314.24   PSIDOT = -284.95   PHITOT =   8.90
              F23 = 2.4626   F12 = 9.8841   PN =  .3629   PNPSI =  .3629   DPHI2 =  .1455E+07
T =  .00060   PHI = 213.39   PHIDOT = 288.40   G =-.0061   PSID = 314.20   PSIDOT = -287.74   PHITOT =   8.94
              F23 = 2.4636   F12 = 9.8856   PN =  .3601   PNPSI =  .3601   DPHI2 =  .1455E+07
T =  .00060   PHI = 213.43   PHIDOT = 292.05   G =-.0060   PSID = 314.15   PSIDOT = -290.51   PHITOT =   8.98
              F23 = 2.4628   F12 = 9.8844   PN =  .3589   PNPSI =  .3589   DPHI2 =  .1464E+07
T =  .00060   PHI = 213.47   PHIDOT = 295.68   G =-.0058   PSID = 314.11   PSIDOT = -293.22   PHITOT =   9.02
              F23 = 2.7208   F12 = 9.9012   PN =  .3388   PNPSI =  .3388   DPHI2 =  .1375E+07
T =  .00061   PHI = 213.52   PHIDOT = 299.11   G =-.0057   PSID = 314.07   PSIDOT = -295.72   PHITOT =   9.06
              F23 = 2.7200   F12 = 9.9000   PN =  .3376   PNPSI =  .3376   DPHI2 =  .1383E+07
T =  .00061   PHI = 213.56   PHIDOT = 302.59   G =-.0055   PSID = 314.03   PSIDOT = -298.22   PHITOT =   9.11
              F23 = 2.7245   F12 = 9.8978   PN =  .3392   PNPSI =  .3392   DPHI2 =  .1406E+07
T =  .00061   PHI = 213.60   PHIDOT = 306.11   G =-.0054   PSID = 313.99   PSIDOT = -300.74   PHITOT =   9.15
              F23 = 2.7236   F12 = 9.8965   PN =  .3380   PNPSI =  .3380   DPHI2 =  .1415E+07
T =  .00061   PHI = 213.65   PHIDOT = 309.67   G =-.0052   PSID = 313.94   PSIDOT = -303.26   PHITOT =   9.19
              F23 = 2.7281   F12 = 9.8943   PN =  .3396   PNPSI =  .3396   DPHI2 =  .1439E+07
T =  .00062   PHI = 213.69   PHIDOT = 313.27   G =-.0051   PSID = 313.90   PSIDOT = -305.80   PHITOT =   9.24
              F23 = 2.7273   F12 = 9.8930   PN =  .3384   PNPSI =  .3384   DPHI2 =  .1448E+07
T =  .00062   PHI = 213.74   PHIDOT = 316.91   G =-.0049   PSID = 313.85   PSIDOT = -308.34   PHITOT =   9.28
              F23 = 2.7319   F12 = 9.8907   PN =  .3400   PNPSI =  .3400   DPHI2 =  .1472E+07
T =  .00062   PHI = 213.78   PHIDOT = 320.59   G =-.0048   PSID = 313.81   PSIDOT = -310.89   PHITOT =   9.33
              F23 = 2.7310   F12 = 9.8893   PN =  .3387   PNPSI =  .3387   DPHI2 =  .1481E+07
T =  .00062   PHI = 213.83   PHIDOT = 324.31   G =-.0046   PSID = 313.77   PSIDOT = -313.45   PHITOT =   9.38
              F23 = 2.7357   F12 = 9.8869   PN =  .3403   PNPSI =  .3403   DPHI2 =  .1507E+07
T =  .00063   PHI = 213.88   PHIDOT = 328.08   G =-.0045   PSID = 313.72   PSIDOT = -316.02   PHITOT =   9.42
              F23 = 2.7348   F12 = 9.8855   PN =  .3389   PNPSI =  .3389   DPHI2 =  .1516E+07
T =  .00063   PHI = 213.92   PHIDOT = 331.90   G =-.0043   PSID = 313.67   PSIDOT = -318.60   PHITOT =   9.47
              F23 = 2.7396   F12 = 9.8830   PN =  .3406   PNPSI =  .3406   DPHI2 =  .1542E+07
T =  .00063   PHI = 213.97   PHIDOT = 335.75   G =-.0042   PSID = 313.63   PSIDOT = -321.18   PHITOT =   9.52
              F23 = 2.7386   F12 = 9.8816   PN =  .3392   PNPSI =  .3392   DPHI2 =  .1552E+07
T =  .00063   PHI = 214.02   PHIDOT = 339.66   G =-.0040   PSID = 313.58   PSIDOT = -323.78   PHITOT =   9.57
              F23 = 2.7435   F12 = 9.8790   PN =  .3408   PNPSI =  .3408   DPHI2 =  .1579E+07
T =  .00064   PHI = 214.07   PHIDOT = 343.60   G =-.0038   PSID = 313.54   PSIDOT = -326.38   PHITOT =   9.61
              F23 = 2.7425   F12 = 9.8775   PN =  .3393   PNPSI =  .3393   DPHI2 =  .1590E+07
T =  .00064   PHI = 214.12   PHIDOT = 347.60   G =-.0037   PSID = 313.49   PSIDOT = -328.99   PHITOT =   9.66
              F23 = 2.7381   F12 = 9.0182   PN =  .3397   PNPSI =  .3397   DPHI2 =  .1610E+07
T =  .00064   PHI = 214.17   PHIDOT = 351.63   G =-.0035   PSID = 313.44   PSIDOT = -331.59   PHITOT =   9.71
              F23 = 2.7371   F12 = 9.0169   PN =  .3381   PNPSI =  .3381   DPHI2 =  .1621E+07
T =  .00064   PHI = 214.22   PHIDOT = 355.70   G =-.0033   PSID = 313.39   PSIDOT = -334.20   PHITOT =   9.76
              F23 = 2.7342   F12 = 9.0121   PN =  .3387   PNPSI =  .3387   DPHI2 =  .1643E+07
T =  .00065   PHI = 214.27   PHIDOT = 359.81   G =-.0032   PSID = 313.35   PSIDOT = -336.81   PHITOT =   9.82
              F23 = 2.7332   F12 = 9.0107   PN =  .3371   PNPSI =  .3371   DPHI2 =  .1654E+07
T =  .00065   PHI = 214.32   PHIDOT = 363.97   G =-.0030   PSID = 313.30   PSIDOT = -339.42   PHITOT =   9.87
              F23 = 2.7302   F12 = 9.0059   PN =  .3376   PNPSI =  .3376   DPHI2 =  .1677E+07
T =  .00065   PHI = 214.37   PHIDOT = 368.17   G =-.0028   PSID = 313.25   PSIDOT = -342.03   PHITOT =   9.92
              F23 = 2.7291   F12 = 9.0044   PN =  .3359   PNPSI =  .3359   DPHI2 =  .1689E+07
T =  .00065   PHI = 214.43   PHIDOT = 372.42   G =-.0026   PSID = 313.20   PSIDOT = -344.64   PHITOT =   9.97
              F23 = 2.7261   F12 = 8.9994   PN =  .3364   PNPSI =  .3364   DPHI2 =  .1713E+07
T =  .00066   PHI = 214.48   PHIDOT = 376.70   G =-.0025   PSID = 313.15   PSIDOT = -347.24   PHITOT =  10.03
              F23 = 2.7250   F12 = 8.9980   PN =  .3347   PNPSI =  .3347   DPHI2 =  .1724E+07
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    T =  .05067   PHI = 211.72   PHIDOT = 799.88   PSI = 315.97   PSIDOT =  673.88   PHITOT =1480.00
                  FF12 = 10.610   FF23 =  2.403
VP=  69.305   VS= -92.570

    IMPACT

                 PHI= 211.724   PHIDOT= 106.890   PSI= 315.966   PSIDOT=-120.280   PHITOT=1479.996
VP= -12.370   VS= -12.370

    COUPLED MOTION
    T =  .05067   PHI = 211.72   PHIDOT = 106.89   G =-.0117   PSID = 315.96   PSIDOT = -120.28   PHITOT =1480.00
                  F23 = 2.6106   F12 =10.9917   PN =  .4276   PNPSI =  .4276   DPHI2 =   .1235E+07
    T =  .05068   PHI = 211.79   PHIDOT = 119.27   G =-.0115   PSID = 315.89   PSIDOT = -133.59   PHITOT =1480.06
                  F23 = 2.6118   F12 =10.9917   PN =  .4230   PNPSI =  .4230   DPHI2 =   .1236E+07
    T =  .05069   PHI = 211.86   PHIDOT = 131.74   G =-.0113   PSID = 315.81   PSIDOT = -146.80   PHITOT =1480.13
                  F23 = 2.6099   F12 =10.9868   PN =  .4210   PNPSI =  .4210   DPHI2 =   .1251E+07
    T =  .05070   PHI = 211.94   PHIDOT = 144.28   G =-.0110   PSID = 315.72   PSIDOT = -159.86   PHITOT =1480.21
                  F23 = 2.6115   F12 =10.9873   PN =  .4155   PNPSI =  .4155   DPHI2 =   .1252E+07
    T =  .05071   PHI = 212.03   PHIDOT = 156.93   G =-.0107   PSID = 315.63   PSIDOT = -172.80   PHITOT =1480.30
                  F23 = 2.6092   F12 =10.9818   PN =  .4131   PNPSI =  .4131   DPHI2 =   .1270E+07
    T =  .05072   PHI = 212.12   PHIDOT = 168.98   G =-.0104   PSID = 315.53   PSIDOT = -184.82   PHITOT =1480.39
                  F23 = 2.8882   F12 =10.9916   PN =  .3950   PNPSI =  .3950   DPHI2 =   .1219E+07
    T =  .05073   PHI = 212.22   PHIDOT = 181.17   G =-.0101   PSID = 315.42   PSIDOT = -196.72   PHITOT =1480.49
                  F23 = 2.8856   F12 =10.9858   PN =  .3923   PNPSI =  .3923   DPHI2 =   .1238E+07
    T =  .05074   PHI = 212.33   PHIDOT = 193.76   G =-.0097   PSID = 315.30   PSIDOT = -208.77   PHITOT =1480.60
                  F23 = 2.8976   F12 =10.9777   PN =  .3974   PNPSI =  .3974   DPHI2 =   .1295E+07
    T =  .05075   PHI = 212.44   PHIDOT = 206.71   G =-.0093   PSID = 315.18   PSIDOT = -220.89   PHITOT =1480.71
                  F23 = 2.8945   F12 =10.9712   PN =  .3942   PNPSI =  .3942   DPHI2 =   .1318E+07
    T =  .05075   PHI = 212.50   PHIDOT = 213.49   G =-.0091   PSID = 315.11   PSIDOT = -227.15   PHITOT =1480.77
                  F23 = 2.9132   F12 =10.9650   PN =  .4033   PNPSI =  .4033   DPHI2 =   .1381E+07
    T =  .05076   PHI = 212.56   PHIDOT = 220.40   G =-.0089   PSID = 315.05   PSIDOT = -233.45   PHITOT =1480.84
                  F23 = 2.9115   F12 =10.9615   PN =  .4015   PNPSI =  .4015   DPHI2 =   .1394E+07
    T =  .05076   PHI = 212.63   PHIDOT = 227.44   G =-.0087   PSID = 314.98   PSIDOT = -239.79   PHITOT =1480.90
                  F23 = 2.9185   F12 =10.9566   PN =  .4043   PNPSI =  .4043   DPHI2 =   .1430E+07
    T =  .05077   PHI = 212.69   PHIDOT = 234.59   G =-.0085   PSID = 314.91   PSIDOT = -246.15   PHITOT =1480.97
                  F23 = 2.9167   F12 =10.9528   PN =  .4023   PNPSI =  .4023   DPHI2 =   .1444E+07
    T =  .05077   PHI = 212.76   PHIDOT = 241.88   G =-.0082   PSID = 314.84   PSIDOT = -252.56   PHITOT =1481.03
                  F23 = 2.9242   F12 =10.9475   PN =  .4052   PNPSI =  .4052   DPHI2 =   .1483E+07
    T =  .05078   PHI = 212.83   PHIDOT = 249.30   G =-.0080   PSID = 314.76   PSIDOT = -258.98   PHITOT =1481.11
                  F23 = 2.9222   F12 =10.9436   PN =  .4030   PNPSI =  .4030   DPHI2 =   .1498E+07
    T =  .05078   PHI = 212.91   PHIDOT = 256.87   G =-.0077   PSID = 314.69   PSIDOT = -265.45   PHITOT =1481.18
                  F23 = 2.6393   F12 =10.9399   PN =  .4037   PNPSI =  .4037   DPHI2 =   .1529E+07
    T =  .05079   PHI = 212.98   PHIDOT = 264.57   G =-.0075   PSID = 314.61   PSIDOT = -271.93   PHITOT =1481.25
                  F23 = 2.6374   F12 =10.9357   PN =  .4013   PNPSI =  .4013   DPHI2 =   .1545E+07
    T =  .05079   PHI = 213.06   PHIDOT = 272.31   G =-.0072   PSID = 314.53   PSIDOT = -278.34   PHITOT =1481.33
                  F23 = 2.6391   F12 =10.9370   PN =  .3957   PNPSI =  .3957   DPHI2 =   .1547E+07
    T =  .05080   PHI = 213.14   PHIDOT = 280.11   G =-.0070   PSID = 314.45   PSIDOT = -284.68   PHITOT =1481.41
                  F23 = 2.6371   F12 =10.9326   PN =  .3931   PNPSI =  .3931   DPHI2 =   .1564E+07
    T =  .05080   PHI = 213.22   PHIDOT = 287.95   G =-.0067   PSID = 314.37   PSIDOT = -290.93   PHITOT =1481.49
                  F23 = 2.6389   F12 =10.9341   PN =  .3872   PNPSI =  .3872   DPHI2 =   .1566E+07
    T =  .05081   PHI = 213.30   PHIDOT = 295.85   G =-.0064   PSID = 314.29   PSIDOT = -297.11   PHITOT =1481.57
                  F23 = 2.6368   F12 =10.9296   PN =  .3845   PNPSI =  .3845   DPHI2 =   .1584E+07
    T =  .05081   PHI = 213.39   PHIDOT = 303.40   G =-.0061   PSID = 314.20   PSIDOT = -302.81   PHITOT =1481.66
                  F23 = 2.9186   F12 =10.9421   PN =  .3661   PNPSI =  .3661   DPHI2 =   .1522E+07
    T =  .05082   PHI = 213.47   PHIDOT = 311.01   G =-.0058   PSID = 314.11   PSIDOT = -308.43   PHITOT =1481.75
                  F23 = 2.9163   F12 =10.9375   PN =  .3634   PNPSI =  .3634   DPHI2 =   .1540E+07
    T =  .05082   PHI = 213.56   PHIDOT = 318.81   G =-.0055   PSID = 314.02   PSIDOT = -314.10   PHITOT =1481.84
                  F23 = 2.9260   F12 =10.9308   PN =  .3670   PNPSI =  .3670   DPHI2 =   .1592E+07
    T =  .05083   PHI = 213.66   PHIDOT = 326.77   G =-.0052   PSID = 313.93   PSIDOT = -319.79   PHITOT =1481.93
                  F23 = 2.9236   F12 =10.9260   PN =  .3641   PNPSI =  .3641   DPHI2 =   .1612E+07
    T =  .05083   PHI = 213.75   PHIDOT = 334.93   G =-.0049   PSID = 313.84   PSIDOT = -325.54   PHITOT =1482.02
                  F23 = 2.9337   F12 =10.9188   PN =  .3677   PNPSI =  .3677   DPHI2 =   .1668E+07
    T =  .05084   PHI = 213.85   PHIDOT = 343.27   G =-.0046   PSID = 313.75   PSIDOT = -331.30   PHITOT =1482.12
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T =  .05084   PHI = 213.95   PHIDOT = 351.82   G =-.0042   PSID = 313.65   PSIDOT = -337.11   PHITOT =1482.22
              F23 = 2.9417   F12 =10.9060   PN =  .3681   PNPSI =  .3681   DPHI2 =   .1749E+07
T =  .05085   PHI = 214.05   PHIDOT = 360.56   G =-.0039   PSID = 313.55   PSIDOT = -342.93   PHITOT =1482.32
              F23 = 2.9390   F12 =10.9007   PN =  .3646   PNPSI =  .3646   DPHI2 =   .1771E+07
T =  .05085   PHI = 214.16   PHIDOT = 369.54   G =-.0035   PSID = 313.45   PSIDOT = -348.81   PHITOT =1482.43
              F23 = 2.9500   F12 =10.8924   PN =  .3683   PNPSI =  .3683   DPHI2 =   .1835E+07
T =  .05086   PHI = 214.26   PHIDOT = 378.71   G =-.0032   PSID = 313.35   PSIDOT = -354.70   PHITOT =1482.54
              F23 = 2.9470   F12 =10.8867   PN =  .3645   PNPSI =  .3645   DPHI2 =   .1860E+07
T =  .05086   PHI = 214.37   PHIDOT = 388.14   G =-.0028   PSID = 313.25   PSIDOT = -360.63   PHITOT =1482.65
              F23 = 2.6630   F12 =10.8831   PN =  .3627   PNPSI =  .3627   DPHI2 =   .1898E+07
T =  .05087   PHI = 214.48   PHIDOT = 397.73   G =-.0024   PSID = 313.15   PSIDOT = -366.53   PHITOT =1482.76
              F23 = 2.6602   F12 =10.8771   PN =  .3586   PNPSI =  .3586   DPHI2 =   .1924E+07
T =  .05087   PHI = 214.60   PHIDOT = 407.37   G =-.0021   PSID = 313.04   PSIDOT = -372.27   PHITOT =1482.87
              F23 = 2.6629   F12 =10.8800   PN =  .3499   PNPSI =  .3499   DPHI2 =   .1924E+07
T =  .05088   PHI = 214.72   PHIDOT = 417.10   G =-.0017   PSID = 312.93   PSIDOT = -377.90   PHITOT =1482.99
              F23 = 2.6600   F12 =10.8739   PN =  .3456   PNPSI =  .3456   DPHI2 =   .1951E+07
T =  .05088   PHI = 214.84   PHIDOT = 426.45   G =-.0013   PSID = 312.82   PSIDOT = -382.98   PHITOT =1483.11
              F23 = 2.9477   F12 =10.8867   PN =  .3274   PNPSI =  .3274   DPHI2 =   .1895E+07
T =  .05089   PHI = 214.96   PHIDOT = 435.92   G =-.0008   PSID = 312.71   PSIDOT = -387.96   PHITOT =1483.24
              F23 = 2.9445   F12 =10.8807   PN =  .3231   PNPSI =  .3231   DPHI2 =   .1921E+07
T =  .05089   PHI = 215.09   PHIDOT = 445.67   G =-.0004   PSID = 312.60   PSIDOT = -393.00   PHITOT =1483.36
              F23 = 2.9576   F12 =10.8706   PN =  .3270   PNPSI =  .3270   DPHI2 =   .2000E+07
T =  .05090   PHI = 215.22   PHIDOT = 455.67   G = .0000   PSID = 312.49   PSIDOT = -398.03   PHITOT =1483.49
              F23 = 2.9542   F12 =10.8642   PN =  .3223   PNPSI =  .3223   DPHI2 =   .2029E+07

FREE MOTION

T =  .05090   PHI = 133.40   PHIDOT = 455.67   PSI =  45.42   PSIDOT = -398.03   PHITOT =1483.49
              FF12 = 10.608   FF23 =  2.796
T =  .05090   PHI = 133.47   PHIDOT = 464.93   PSI =  45.36   PSIDOT = -396.20   PHITOT =1483.56
              FF12 = 10.589   FF23 =  2.549
T =  .05090   PHI = 133.53   PHIDOT = 474.26   PSI =  45.31   PSIDOT = -394.37   PHITOT =1483.62
              FF12 = 10.588   FF23 =  2.549
T =  .05090   PHI = 133.60   PHIDOT = 483.55   PSI =  45.25   PSIDOT = -392.53   PHITOT =1483.69
              FF12 = 10.595   FF23 =  2.553
T =  .05091   PHI = 133.67   PHIDOT = 492.81   PSI =  45.19   PSIDOT = -390.70   PHITOT =1483.76
              FF12 = 10.594   FF23 =  2.553
T =  .05091   PHI = 133.74   PHIDOT = 502.03   PSI =  45.14   PSIDOT = -388.87   PHITOT =1483.83
              FF12 = 10.634   FF23 =  2.834
T =  .05091   PHI = 133.82   PHIDOT = 511.14   PSI =  45.08   PSIDOT = -387.03   PHITOT =1483.91
              FF12 = 10.633   FF23 =  2.833
T =  .05091   PHI = 133.89   PHIDOT = 519.86   PSI =  45.03   PSIDOT = -385.20   PHITOT =1483.98
              FF12 = 10.626   FF23 =  2.840
T =  .05092   PHI = 133.96   PHIDOT = 528.63   PSI =  44.97   PSIDOT = -383.36   PHITOT =1484.06
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T =  .05092   PHI = 134.04   PHIDOT = 537.48   PSI =  44.92   PSIDOT = -381.53   PHITOT =1484.13
              FF12 =  9.699   FF23 =  2.840
T =  .05092   PHI = 134.12   PHIDOT = 546.37   PSI =  44.86   PSIDOT = -379.69   PHITOT =1484.21
              FF12 =  9.698   FF23 =  2.839
T =  .05092   PHI = 134.20   PHIDOT = 555.31   PSI =  44.81   PSIDOT = -377.86   PHITOT =1484.29
              FF12 =  9.689   FF23 =  2.834
T =  .05093   PHI = 134.28   PHIDOT = 564.29   PSI =  44.75   PSIDOT = -376.02   PHITOT =1484.37
              FF12 =  9.689   FF23 =  2.834
T =  .05093   PHI = 134.36   PHIDOT = 573.32   PSI =  44.70   PSIDOT = -374.19   PHITOT =1484.45
              FF12 =  9.680   FF23 =  2.829
T =  .05093   PHI = 134.44   PHIDOT = 582.38   PSI =  44.65   PSIDOT = -372.35   PHITOT =1484.53
              FF12 =  9.679   FF23 =  2.828
T =  .05093   PHI = 134.53   PHIDOT = 591.51   PSI =  44.59   PSIDOT = -370.52   PHITOT =1484.62
              FF12 =  9.670   FF23 =  2.823
T =  .05094   PHI = 134.61   PHIDOT = 600.67   PSI =  44.54   PSIDOT = -368.68   PHITOT =1484.70
              FF12 =  9.669   FF23 =  2.823
T =  .05094   PHI = 134.70   PHIDOT = 609.88   PSI =  44.49   PSIDOT = -366.85   PHITOT =1484.79
              FF12 =  9.660   FF23 =  2.817
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               FF12 =   9.659  FF23 =   2.817
T =   .05094   PHI = 134.83   PHIDOT = 623.50   PSI =  44.41   PSIDOT = -364.09   PHITOT =1484.92
               FF12 = 10.543   FF23 =   2.390
T =   .05094   PHI = 134.88   PHIDOT = 627.81   PSI =  44.38   PSIDOT = -363.18   PHITOT =1484.97
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T =   .05094   PHI = 134.92   PHIDOT = 632.10   PSI =  44.36   PSIDOT = -362.26   PHITOT =1485.01
               FF12 = 10.547   FF23 =   2.393

 F23MAX =   3.41

 F12MAX = 11.95

 FF23MAX =  3.08

 FF12MAX = 11.48

 PNMAX =    .69

NUMBER OF TURNS TO ARM=  25.472
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